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Detection of harmonics produced by over excited induction generators /

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DETECTION OF HARMONICS PRODUCED BY

OVER EXCITED INDUCTION GENERATORS

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ABSTRACT

The presence of harmonics on the power system is very undesirable. In addition to the adverse effect they have on system apparatus, harmonics may also be detrimental to customers. Their effect on system apparatus range from decreased lifetime for transformers and capacitors to failure to interrupt fault current for circuit breakers. The effect harmonics have on customers is most noticeable in communication channels, where harmonics induce undesirable noise.

Harmonics are produced whenever there is a non-linear relationship between voltage and current. Common sources of harmonics include arc furnaces, high voltage electronic AC/DC converters and overexcited transformers. Most sources of harmonics on the power system are usually identifiable and actions can be taken to minimize any effects these installations may have on the system, such as the installation of harmonic filters. In some situations, however, harmonics are generated in conditions which cannot always be accurately

predicted, such as overexcited transformers. Usually the voltage on the power system is tightly controlled so the probability of transformers becoming overexcited is very small.

However, there are instances when induction generators may produce overvoltages when becoming separated from the power system. These overvoltages may produce harmonics due to the non-linear voltage-current characteristics present in transformers on the system. The voltage-current characteristics of transformers become non-linear because at sufficiently high voltages the iron in the core goes into saturation. The protective relaying which presently exists to detect overexcitation of induction generators may also be adversely affected by the presence of harmonics in the waveform. Sometimes the affects are so severe that relays may fail to operate, allowing the overexcited generator to keep generating a very distorted waveform.

There presently exists a need for a relay scheme which can accurately determine when excessive harmonics are being produced by overexcited induction generators. This paper analyzes the behavior of overexcited induction generators and outlines a relay circuit which should be more accurate in detecting this condition than the relay schemes presently used.

CHAPTER 1

POWER SYSTEM HARMONICS: THEIR EFFECTS ON THE POWER SYSTEM AND SOURCES

The adverse effects of harmonics which may propagate throughout a power system are numerous, some of which have been known since the 1930s. Excessive harmonics on power systems have been known to cause inductive interference with communication systems, failures of capacitor banks, dielectric breakdown of insulated cables, errors in induction meters, relay malfunctions, and excessive heating of induction and synchronous machines.[1] The effects harmonics have are often dependent upon their source and the network characteristics of the system through which the harmonics are propagating. It is these characteristics which directly influence the magnitude of the harmonics. If the system impedance seen by a harmonic source exhibits a characteristic frequency at the same frequency as a specific harmonic (resonance condition), the magnitude of that specific harmonic in the system will increase dramatically, since the impedance of the circuit for that particular harmonic is theoretically zero (the limiting factors on the harmonics are its source strength and circuit resistance).[2]

The first area in which the adverse effects of harmonics was noticed was that of interference in communication channels. The way in which harmonics interfere with telephone channels is by the magnetic coupling present between any telephone line and any nearby power conductors. This is known as inductive interference since it is the time varying electric current which is inducing a voltage in the communication circuit, due to its respective changing flux, which casues the interference. The magnitude of voltage which will be induced into the communication circuit is given by the following equation[3]:

$$v(t) = -M\frac{dI}{dt}\cos(\alpha) \qquad (1)$$

where M is defined as the mutual induction between the two conductors, which is found to vary with frequency and conductor separation, α is defined as the angle at which the two conductors cross, and dI/dt is defined as the complex time varying current. From equation (1), the $\cos(\alpha)$ term indicates that maximum inductive interference will occur when the two conductors are parallel ($\alpha=0$, $\cos(0)=1$) and that conductors which are perpendicular will not be affected ($\alpha = \pi/2$,

$\cos \pi/2=0$). It is also interesting to note that the normal 60 Hz power signal will also induce a voltage into any accompanying telephone circuit. The existence of this induced 60 Hz signal is not, however, of immediate concern for two reasons. One, although audible (as 60 Hz hum), it is not within the frequency range of voice communication. Secondly, if this 60 cycle hum becomes too irritating it may easily be removed with rejection filters.[4] Harmonics of power system signals, on the other hand, may affect the quality of transmission, since the harmonic may fall within the frequency range of voice communication (depending on the order of the harmonic). For normal telephone communication, frequencies up to 3 kHz are considered to be the most sensitive to the human ear.[5] Any attempts to filter out these harmonics, therefore, would prove impractical since the voice information existing at the harmonic would be lost. Further, unless the exact value of the harmonic which is causing the interference is known, separate filters for each possible harmonic would be required. Therefore, the only solution is to prevent any harmonics from inducing interference in the communication channel. This prevention may be achieved by controlling the existence and flow of harmonics on the affected power system. The methods which have been developed to control this type of interference are not pertinent to this paper.

The next area in which harmonics make their presence noticeable is in relation to standard power system equipment. The equipment most susceptible to damage from harmonics include capacitors, switchgear, and transformers. Although these devices are most susceptible to the adverse effects, almost every device connected to, or associated with, the power system is vulnerable to damage or malfunction due to the presence of harmonics on the power system.

Capacitors are probably the most affected by harmonics, since it is their presence on the power system which greatly influence the flow, and most importantly, magnitude of harmonics. The low impedance path that they offer harmonics is considered to be the factor which often makes the magnitude of harmonic power flows greater than what they normally would be, had the capacitor not been present on the system. Also, there exists the possibility that the presence of a capacitor may create a resonance condition for a harmonic which already exists, making a bad situation even worse.[6] It is possible, depending upon the phase relationship between the fundamental voltage and the harmonic voltage present due to the increased harmonic power flows, for the peak voltage across the capacitor to be 10% above its nominal rating, even though its RMS value may be below 110% of the nominal rating. This excessive peak-to-peak voltage may affect the useful life of the capacitor, in addition to the harmonics producing excessive reactive power (VARs).[7]

As stated above, power transformers are also greatly affected by the presence of harmonics. Unlike the situation associated with capacitors, as described above, it has been found that there is one harmonic, the third harmonic, which is more prevalent than the others, which affects the performance of power transformers. Additionally, the effects of this third harmonic have been found to be much more pronounced in shell-type constructed transformers than in the core-type transformers since the third harmonic is usually present as a result of transformer design.[8] However, recent changes in the philosophy of the transformer design has made both types of transformers much more susceptible to harmonics, and, in some cases the design of transformers has been found to actually generate harmonics. In the past, there was a tendency to "over design" transformers. Now, with cost a primary factor, transformer operating points are being designed up to the edge of, sometimes even falling into, the non-linear region of the iron core magnetic characteristic.[9] As will be discussed later in this paper, this current trend in transformer design may also cause harmonics to flow, depending upon the transformer's excitation. Any significant presence of harmonic currents will cause additional heat in the windings and increase stray flux losses. A further consequence of the presence of harmonics is the possibility of resononace between the transformer windings and the system capacitances. Transformers have been known to fail as a result of the additional heat and iron losses caused by the presence of harmonics.[10]

Power system switching apparatus is also subjected to harmonics. The effects of harmonics on switchgear range from increased heating as is the case with transformers, to possible failure to interrupt currents.[11] There are documented cases where air-magnetic circuit breakers have failed to interrupt currents having high harmonic current. The breaker's blowout coil is not designed to operate with high amounts of harmonics in the current. It is the function of the blowout coil to aid the arc's movement into the arc chute where the interruption takes place. It has been determined that the high harmonic content of the current (approximately 50%) causes inefficient operation of the blowout coil which results in prolonged arcing and, eventually, breaker failure. Vacuum circuit breakers are less sensitive to harmonic distortion.[12]

Until the advent of solid state relays, the effect harmonics had on protective relays was never considered. The development of static relays initiated the investigation into the effects distorted waveforms have on protective relays, electromechanical as well as solid state. Electromechanical relays depend upon magnetic fluxes producing a torque resulting in some type of movement of a relay mechanism (magnetic disk, induction cup, cylinder, or plunger). The device is designed to close or open its contacts after a torque of selected minimum quantity has caused the relay mechanism to travel a predetermined distance. This torque is usually proportional to an input voltage, current, or combination of both. Some relays are considered instantaneous, in that it only requires the presence of the magnetic torque a few hundredths of a second to move the relay mechanism (induction cup, cylinder, or plunger) far enough to operate its contacts. Other relays are considered inverse time relays in that the operating time delay of the relay mechanism (usually an induction disk) is inversely proportional to the magnitude of the applied magnetic torque.[13] These relays are designed so that these time delays can be quite predictable, allowing the system relay engineer to accurately determine how long it will take the relay to operate. This is necessary when determining whether or not coordination between relays on adjacent lines exists.

The initial studies into the effects of harmonics on protective relays found that harmonics on the power system do affect protective relays, both electro-mechanical and solid state. It was found that electro-mechanical relays which were single input devices, utilizing phase shifting circuitry to obtain a quadrature flux to achieve torque, operated less efficiently when the input signal (voltage or current) contained distorted frequencies. The reason for this slower operating time is the fact that the circuitry providing the quadrature flux is optimized for one frequency.[14] On induction disk relays, counteracting this slower operation due to circuit design is the fact that the synchronous speed of the disk is proportional to frequency. Therefore waveforms with high frequency components should cause the disk to rotate faster.[15] However, tests on some relays have shown that this is not always the case. Some harmonics, instead of increasing the speed of the disk, merely increase heating in the relay.[16] Multi-input relays are relays which use two, or possibly more, inputs to achieve magnetic torque. Two input signals of different frequencies will produce an operating torque which has an average value of zero. Hence if only one signal is distorted, the relay does not exhibit any adverse effect from harmonics, except for maybe some additional heating. However, if both signals contain harmonics, the result may be a chnge in the net torque, positive or negative, depending upon the phase relation between the respective harmonic components of each input signal.[17] In general, it was found that electromechanical relays with high levels of harmonics were more likely to operate slower or with a higher value of pickup than to operate faster or with a lower value of pickup.[18]

Solid state relays take a signal representation of some parameter on the power system, and transform it down to an acceptable level for use in electronic circuits.

Analog electronic circuits then operate on this input to determine whether or not a faulted condition exists on the system. How a solid state relay responds to harmonics is as much a function of its design as anything else. Static relays which operate on peak value of the waveform will respond in a different manner (which is likely to be more noticeable) than those designed to operate on the rms value of the waveform. Static relays which utilize zero-crossing time measurements for frequency analysis will definitely be affected by distorted waveforms. In general, the pickup values and time delays of static relays are affected by harmonics in much the same was that electromechanical relays are affected. This is partly due to the tuned networks present in the electronic circuitry, much like those in the electromechanical realys.[19]

One area of static relaying which is not yet fully developed due to its high cost, is computer or microprocessor based relaying. In this type of static relay, the analog signal is first digitized. The digitized values are then used in computations by the system program. In these types of static relays, the effect of harmonics on the preformance of the relay is determined by the sampling rate of the input signal and software. The software can be programmed to analyze all non-fundamental frequency components up to one-half of the sampling rate. Thus, if a harmonic outside the range of the present computer-based relay is known to exist on that portion of the system where the relay is to be installed, or is found to be causing problems for an existing computer-based relay, the problem can be alleviated by increasing the sampling rate for the A/D conversion and making the appropriate software changes. The only problem with this method is that it adds to the already high cost of the relay.[20]

Although it has been shown that harmonics may have adverse effects on communication channels, the power system, and its associated equipment, their effects on customers should not be ignored. When discussing the effects of harmonics on customers, the customers must be broken down into two basic categories. The first category includes those customers that may cause harmonics to flow (and inessence are responsible for creating their own problems), such as any AC/DC conversion customer (battery chargers, photovoltaics, etc.). The second group would consist of customers who experience adverse effects by harmonics propagating through the system. These customers are not responsible for causing harmonics to flow. The first adverse effect of harmonics which has already been touched upon is telephone interference. However, as stated earlier, this problem has been greatly alleviztted in recent years. If harmonics are present at the customer's meter, his meter may run faster. This is something the customer surely does not want. Also, for residential customers, electric time pieces, both analog and digital, may be affected. One area which may require more study is the effect of harmonics on residential service home computers.

For commercial and industrial customers, the problems may be of a slightly greater significance. For institutions which use harmonics imposed on their local system for master control of clocks, school bells, etc., any leakage of harmonics from the power system into their local system may cause problems with the control of the apparatus.[21] An area which would affect industrial customers is that of the effect on AC motors. Here, there are a multitude of effects, the first of which may be referred to as the 7th, 13th, 19th, ... harmonic effect. When these harmonics are present, positive torque will result. A desirable effect if you want to call it that. The 5th, 11th, 17th, ... harmonics produce a negative torque, a definite undesirable effect. The 3rd, 9th, 15th, ... harmonics produce no torque, only heating in the motor windings.[22] There are documented cases where line currents have operated relays set at twice the maximum power of a machine when the machine was not even close to approaching full load. The problem with one such case was a high magnitude 5th and 7th harmonic current present on the line.[23] Soemtimes, however, a customer's load when connected to the system may appear as a parallel resonance to a harmonic.[24] In that case, the customer actually causes his own problem, thus placing him in with the group of customers which cause harmonic flows. These types of problems indicate that the effects of excessive harmonics do go beyond the power system to the customers.

Having determined that harmonics on the power system may have a detrimental effect, not only to the electric utilities, but customers as well, the next thing was to identify the potential major sources of harmonics and protect the system from their infiltration. The main cause of harmonics is networks which contain non-linear circuit parameters.[25] The non-linear circuit parameters causing the distorted waveform may be a saturated magnetic core, a ferroresonance condition existing in a magentic core, allowing current to flow only for limited periods of time during the sinusoidal excitation, or merely non-linear volt-amp characteristics. The effect each non-linear load has on the current and voltage waveforms is a function of each individual installation, although some groups of equipment as a whole tend to exhibit certain characteristics unique to that type of installation. For example, the harmonics generated by two different arc furnaces will not be exactly the same, but the predominant harmonics will probably be very close in order or the same.

The first significant source of harmonics to appear on the power system were arc furnaces. Arc furnaces cause distorted waveforms due to the nature of their operation. Using an electric current to melt materials, usually metals, the current-voltage characteristics are constantly changing, depending upon the type of material being melted, and the relative composition between the liquid and solid of the material. Studies have indicated that arc furnaces tend to produce distorted waveforms containing predominantly third, fifth, and seventh harmonic components.[26] Since it was found that the harmonics which accompany the installation are rather predictable and not too numerous, it has been possible to significantly reduce the adverse effects of these sources by having the customer generating these harmonics install the appropriate harmonic filters to prevent their infiltration into the power system.

Another major source of harmonics appeared with the advent of high voltage AC/DC converters. The purpose of AC/DC converters is just as its name implies, to either convert an AC voltage to DC voltage or vice versa. AC/DC converters are utilized in HVDC transmission links or batterychargers. DC to AC converters are used at the receiving end of a HVDC transmission link or by DC cogenerating customers for sale to the interconnecting utility.

The initial AC/DC converters were required for HVDC power transmission and were motor-generator sets. In an attempt to eliminate the losses present in a two machine converter, electronic AC/DC converters can now be found with photovoltaic and windmill installations from which the utility is obligated to purchase any excess power these units may produce. The potential for more AC/DC converters exists if, due to market conditions and advancing technology, there is a sudden increase in demand for electric powered vehicles, since the vehicles'batteries will need regular recharging.

In electronic AC/DC conversion, power is transferred between the AC source and the DC source by controlling the time of conduction of devices called thyristors. These devices may be adjusted to conduct for a minimum magnitude of line voltage and not to conduct for voltages below this minimum (line commutation), or their conudction time may be controlled by some other means of control (self-commutation). Each interval of time a thyristor conducts is called a pulse. With a normal three phase supply, and a single three phase transformer, six pulses per cycle may be obtained (one positive and one negative for each phase). The number of pulses may be increased by paralleling transformers with predetermined phase shifts between the different banks.[27] This type of operation has the effect of producing a very chopped current waveform, which contains high levels of harmonics for a normal sinusoidal voltage waveform. Research with these devices has indicated that, like arc furnaces, there are certain harmonics which are characteristic to these installations.

The harmonics which will be present on a power system with these types of AC/DC converters is a function of the number of pulses associated with the converter. The predominant harmonics which will be present are given by equation (2):

$$h = np + 1 \tag{2}$$

where n is defined as the harmonic order and p is defined as the number of pulses. Therefore, since the harmonics which will be present with these types of installations are known, preventing their infiltration into the power system is possible by incorporating the necessary harmonic control techniques into the design of the AC/DC installation. These techniques, whose operation is beyond the scope of this paper, include the use of harmonic filters, a series reactor in series with the utility transformer,[30] and harmonic cancellation transformers.[31] Studies of AC/DC installations utilizing one or more of these techniques have shown just how well harmonics can be kept from entering the power system from a known major source.[32]

A third source of harmonics which has recently evolved is transformer core saturation. With transformers being designed to operate as close to the edge of the nonsaturated portion of the excitation curve as possible, any slight overvoltage may result in a distorted waveform. The explanation for this distorted waveform can be found by examining the saturation curve of a typical distribution transformer, with the abscissa and ordinate axes calibrated in percent of rated voltage and current, respectively. Tests conducted by the Pennsylvania Power and Light Company (PP&L)[33] have found transformer excitation curves similar to the one shown below in FIG. (1).

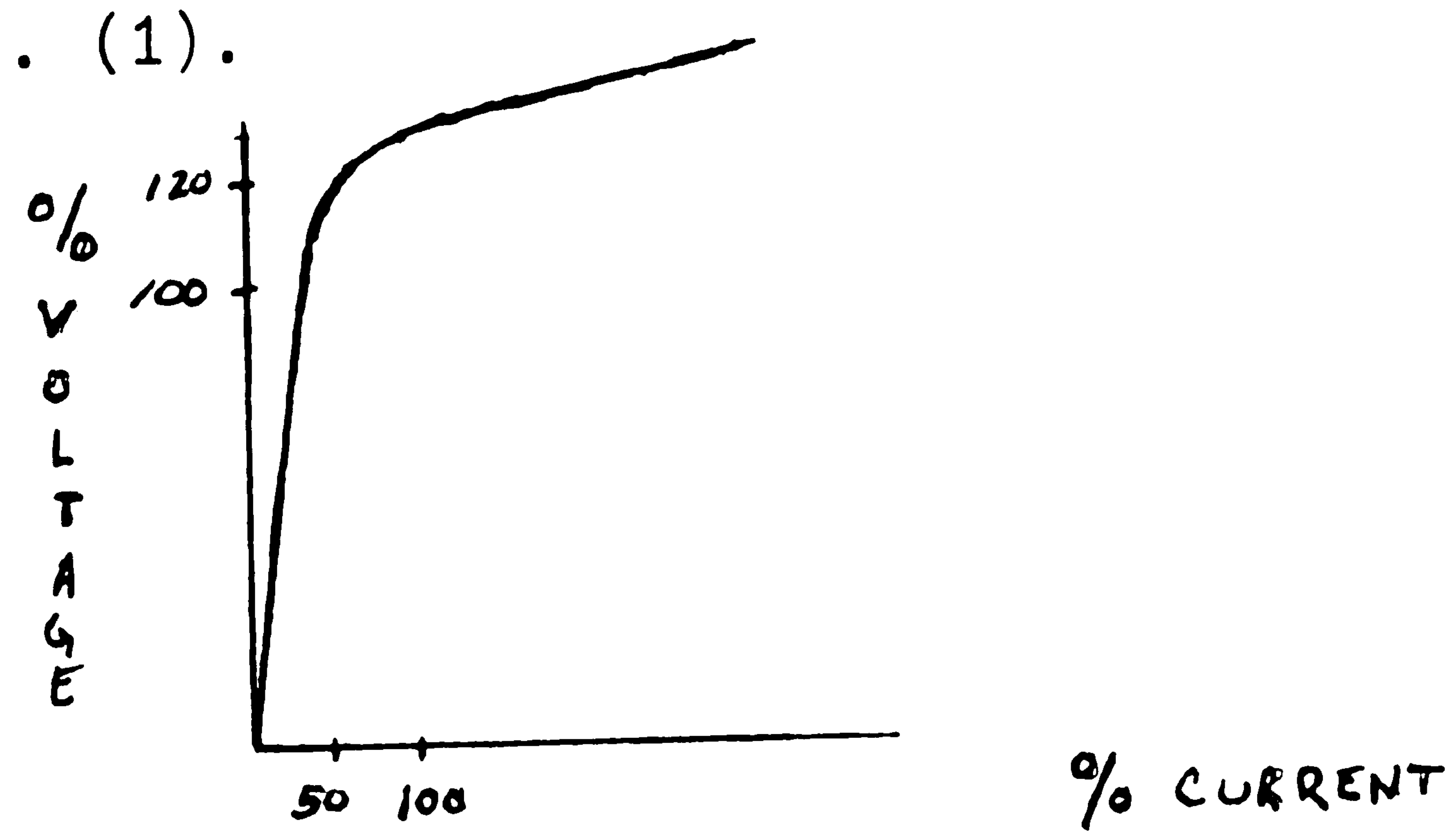


FIG. (1)

How an overexcited transformer may produce a distorted waveform can be visualized by the linear excitation curve shown in FIG. (1). The linear nonsaturated region of the excitation curve very nearly approaches a vertical line. This means that for any voltage within this range which is impressed upon the transformer, the required exciting magnetization current required to align the magnetic particles is a constant value.

Hence, for a sinusoidal excitation with its peak-to-peak voltage within this range, the required magnetizing current is constant. A sinusoidal excitation with peaks beyond this linear range will require additional exciting current. This additional exciting current results in distorted current waveforms, rich in harmonics. The magnitude of current distortion, as well as the harmonic content depends upon the amount of the over-excitation and the v-i characteristics of the particular transformer or iron core device. Since each device is different and the magnitude of overexcitation cannot always be accurately predicted, it is difficult to determine exactly which harmonics will be present at every installation. However, tests have shown that the third harmonic is almost always present with this type of distortion and is always the dominant harmonic.[34]

Another factor which complicates the matter of harmonics from overexcited transformers is ferroresonance. Ferroresonance occurs when the inductive reactance of a magnetic core electrical device equals any capacitive reactance associated with the connected circuit, at any frequency. At this frequency, the total effective reactance of the circuit is zero and essentially appears as a short circuit, allowing high magnitudes of current to flow at that frequency. The inductance of an iron core is variable, since it is a function of the current. Therefore, as its exciting current is changing, the inductance will likewise change, which may create resonances at more than one frequency with the connected capacitances. The resonant frequencies for different transformers are different and difficult to predict since they are dependent upon the magnetic properties of the iron core.[35]

Since transformers are present throughout the system, and their magnetic properties may be dissimilar, determining when and where they will produce a distorted waveform is quite difficult. The one factor which most often leads to distorted waveforms, however, is overexcitation. If the exciting voltage can be maintained at levels which are definitely within their linear region, the problem can be greatly minimized. As will be derived, there are situations beyond the control of electric utilities which may lead to overexcitation of transformers and, therefore, harmonic generation.

CHAPTER 2

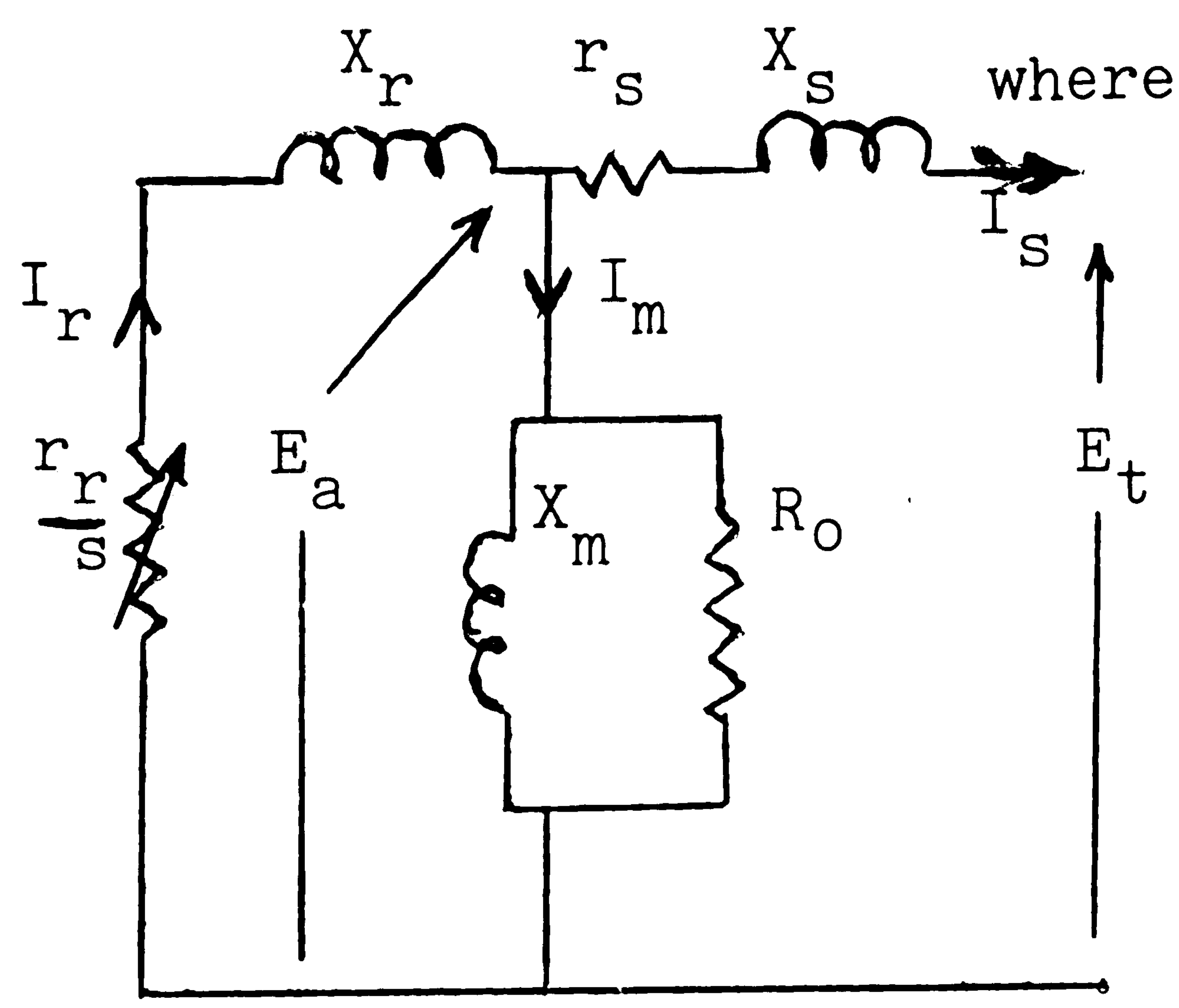
THEORY OF HARMONIC PRODUCTION BY SELF-EXCITED INDUCTION GENERATORS

There are times when the operating voltage of the system may be beyond the linear region of the system transformers' excitation curve. Until recently the chances of this occurring were very slight since the characteristics of the system were well defined. The recent Public Utility Regulatory Policy Act (PURPA) has changed this. The act requires utilities to purchase any excess power which a customer may produce from his own installation which is supplied by an approved type of renewable energy (wind, solar, hydro, etc.) at a fair price to both parties. As a result, customers have been installing their own generators (cogenerators). Often these installations utilize induction generators as their electrical generating device due to their simplicity and relative low cost. An induction generator is basically nothing more than an induction motor driven by some prime mover above synchronous speed. The "excitation" required for the generator usually comes from the connected power system which determines the generated voltage and frequency. Hence, the field and the prime mover controls associated with synchronous machines are not required.[37]

The excitation, or magnetizing VARs, required by the induction generator is usually drawn from a separately excited power system. However, under the right conditions, an induction generator may operate on its own, without a separately energized power system, having its magnetizing current supplied from capacitors.[38] If these capacitors had to be connected right at the terminals of the machine this would not present any great consequence. However, the capacitors which supply the magnetizing VARs for these induction generators may be located anywhere on the system connected to the generator. This is what may cause problems since electric utilities use capacitors throughout their distribution systems for VAR supply and voltage support. As a result of their widespread use, capacitors are often found on distribution circuits which also have these cogenerators connected to them. During the time the line and cogenerator are energized from the power system, the capacitors and cogenerators do not in any way interfere with each other. Problems can develop, however, when a fault occurs on the feeder circuit which contains both capacitors and induction generators.

When a fault occurs on a distribution circuit, fault sensing devices operate to isolate the faulted portion of the line. If the induction generator is located on that portion which has become isolated, it will try to keep supplying power to the line. A permanent fault on the isolated line will bring the terminal voltage of the generator down very quickly, causing its associated undervoltage relays to operate and open the interconnecting circuit breaker, separating the generator from the faulted line. However, if the fault is only a transient one (as is often the case) the induction generator will try to supply the connected load. Frequently in this case, the connected load is great enough so that the generator terminal voltage falls very quickly to a low enough level to operate the undervoltage relays and the interconnecting breaker, again separating the generator from the distribution circuit. However, under the proper combinations of load, connected capacitance and machine characteristics, the generator may become "self-excited", and maintain power flow to the connected load at the proper system voltage and frequency. This presents no real concern to the utility, provided the power being supplied to other customers on that portion of the line is of acceptable quality (is within proper voltage limits and acceptable waveform). Sometimes, however, due to machine and circuit characteristics, the generator terminal voltage may actually increase. This occurrence presents a real concern for utilities. If the voltage increase were to go unchecked, the other customers connected to that circuit would be subject to overvoltage, something which is not desirable for the utility or other customers. Therefore, relays are required to detect this condition so that the generator may be tripped off. However, this overvoltage condition may also cause excessive harmonics due to overexcited transformers. Not only does this further degrade the quality of power being supplied to the other customers, but this may also cause the overvoltage relays to not function,[39] hence the generator will continue to generate and supply unacceptable quality power to the other customers with no means of detection. Although the chances of this condition arising are not great, it is a concern to electric utilities.

The first aspect of this problem which must be addressed is determining what system conditions may lead to the self-excitation of an induction generator, and which of these conditions may result in overexcitation of system transformers and excessive harmonic flows. The equivalent circuit[40] for an induction generator is shown below in FIG. (2). This equivalent model is for all quantities referred to the stator



where X_r=rotor reactance
X_m=magnetizing reactance
X_s=stator reactance
r_s=stator resistance
r_r=rotor resistance
s =slip
E_t=terminal voltage
Ea=air gap voltage
R_o=core loss shunt

FIG. (2)

For most cases, the no load active current can be considered as part of the magnetizing current and the core loss shunt resistance (R_o) can be neglected with little loss in accuracy. The resulting representation is shown in FIG. (3).

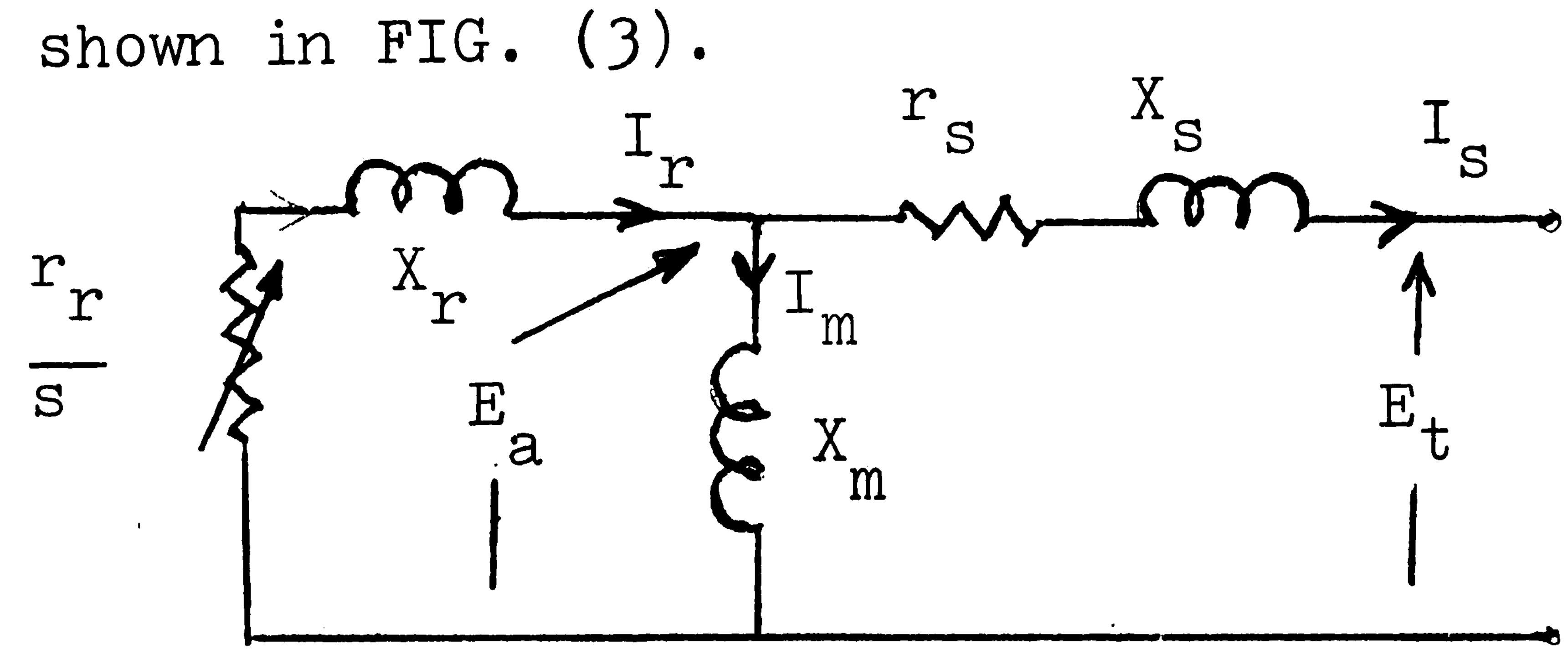


FIG. (3)

With a basic understanding of the operation of induction machines, the method by which an induction generator may become self-excited can be determined by analyzing the above model under loaded and unloaded conditions. When excited by an a-c source, a rotating flux is established in the air gap. When operating as a motor, this rotating flux induces a current and voltage in the rotor and the rotor rotates at some speed less than the synchronous speed of the flux. If the rotor is driven by some prime mover at synchronous speed, no voltage is induced in the rotor since there is no relative motion between it and the revolving magnetic flux. If the speed of the rotor is increased above synchronous speed by the prime mover, there is a reversal in the relative direction of rotation between the rotor and the flux. With this reversal, the voltages and current induced into the rotor are also reversed and power is transferred into the stator. Within the generator there is a flux generated by the current in the rotor[41]. The current in the stator can be broken down into two components. One component is defined as the load current, which produces an mmf within the machine opposite in polarity and equal in magnitude to the flux produced by the rotor current. The remaining component of the stator current is defined as the magnetizing current which is required to create the resultant air gap flux. The resultant air gap flux is a function of the magnitude of the air gap voltage, which is the counter emf generated by the synchronous rotating air gap flux. A study of FIG. (3) shows that the difference between the air gap voltage and the terminal voltage is given by equation (3).[42]

$$E_t = E_a - I_s(r_s + jX_s) \tag{3}$$

and that E_a is defined as

$$E_a = I_m jX_m \tag{4}$$

Although X_m is a function of the air gap voltage, for small voltage variations it is sufficiently accurate to consider X_m a constant.[43] The flux linkages in the rotor are given by equation (5), w=angular frequency:

$$\lambda_r = \frac{I_r(X_r + X_m)}{w} - \frac{I_s X_m}{w} \tag{5}$$

From the model in FIG. (3), I_r can be defined as

$$I_r = I_s + \left[\frac{E_t + I_s(r_s + jX_s)}{jX_m} \right] \qquad (6)$$

Substituting the relation in equation (6) into equation (5) yields

$$\lambda_r = \frac{X_r + X_m}{wjX_m} \left[E_t + I_s(r_s + jX_s + jX_m) - j\frac{X_m^2}{X_r + X_m} \right] ,$$

which reduces to

$$\lambda_r = \frac{X_r + X_m}{wjX_m} \left[E_t + I_s(r_s + jX') \right] , \text{ where} \qquad (7)$$

$$X' = \frac{X_m X_r}{X_m + X_r} + X_s .$$

Also, since there is no separate excitation voltage in the rotor, the sum of the voltage induced by the changing flux linkage and voltage produced by the rotor current and resistance must equal zero[44].

$$I_r r_r + \frac{d\lambda_r}{dt} = 0 \qquad (8)$$

With these basic relationships, the operation of the generator under loaded and unloaded conditions can be analyzed. Let e be defined as the open circuit terminal voltage for a given rotor current I_r ($I_r = I_m$).

For this condition, e can be defined by equation (9) and is equal to the air gap voltage:

$$e = I_r jX_m \ . \tag{9a}$$

Substituting the relation in equation (6) for I_r gives

$$e = E_t + I_s \left[r_s + j(X_s + X_m) \right] \ . \tag{9b}$$

If the generator had an external excitation and the rotor was driven at synchronous speec, (i.e., s=0, no power being generated) this air gap voltage would be defined by rearranging equation (3) to read

$$E_a = E_t + I_s(R_s + jX_s). \tag{10}$$

Let e' be defined as the voltage that would exist at the terminals of the generator immediately after the generator is disconnected from a separately energized power system, while the generator is carrying load. Again, as was the case with the no-load condition, after the generator is isolated from the power system, this voltage is equal to the air gap voltage which was present prior to the disconnection, and was defined in equation (9) as $I_r X_m = E_t = e'$. The flux linkages, λ_r present in the rotor prior to disconnection is given by equation (7). The flux linkages, λ_r, after the generator is disconnected can be found from equation (5) with I_s equal to 0, yielding

$$\lambda_{r_{after}} = \frac{I_r(X_r + X_m)}{w} . \tag{11}$$

From the theory of constant flux linkage it is known that $\lambda_{r_{before}} = \lambda_{r_{after}}$, so

$$\frac{X_r + X_m}{wjX_m}\left[E_t + I_s(R_s + jX')\right]\Bigg|_{t=0^-} = \frac{I_r(X_r + X_m)}{w}\Bigg|_{t=0+}$$

solving for $I_r\Big|_{t=0+}$ yields

$$I_r\Big|_{t=0+} = \left[E_t + I_s(r_s + jX')\right]\frac{1}{jX_m}\Bigg|_{t=0-} . \tag{12}$$

Substituting this value into equation (9) yields

$$e' = \left[E_t + I_s(r_s + jX')\right]\Bigg|_{t=0^-} \tag{13}$$

From equations (7) and (13), the rotor flux linkages can be written as

$$\lambda_r = \frac{e'(X_r + X_m)}{wjX_m} \tag{14}$$

Substituting equations (9) and (14) into (8) yields

$$\frac{e \cdot r_r}{jX_m} + \left[\frac{(X_r + X_m)}{wjX_m}\right]\frac{de'}{dt} = 0 \ , \tag{15}$$

which simplifies to[45]

$$e + \left[\frac{X_r + X_m}{wr_r}\right]\frac{de'}{dt} = 0 \ .$$

This is analogous to the equation used in transient analysis of synchronous machines:

$$e_d + T_{do} \frac{de'_d}{dt} = e_x \ . \tag{16}$$

In our case, e_x=0, e_d and e_d' are similar to e and e', respectively, and T_{do} can be equated to $\frac{X_r+X_m}{wr_r}$ which is commonly referred to as the open circuit transient time constant of the induction machine.[46]

Starting with equation (16) and representing the system and load as a series impedance R + jX, the generator behavior can be analyzed for some remote sectionalizing device isolating it from the rest of the power system. The terminal voltage E_t can now be written as

$$E_t = I_s(R_e + jX_e) \; . \tag{17}$$

Utilizing the relationship in equation (17) and substituting into equation (13), e' can be defined as

$$e' = E_t + \frac{E_t(r_s + jX')}{(R_e + jX_e)} = E_t \left[\frac{R_e + r_s + j(X_e + X')}{R_e + jX_e} \right] . \tag{18}$$

Substituting equation (17) into equation (10) yields the following definition for e

$$e = E_t + \frac{E_t(r_s + jX_s + X_m)}{(R_e + jX_e)} = E_t \left[\frac{R_e + r_s + j(X_e + X_s + X_m)}{R_e + jX_e} \right] . \tag{19}$$

Substituting the new relationship for e and e' into equation (16) yields the following:

$$E_t \left[\frac{R_e + j(X_e + X_s + X_m)}{R_e + jX_e} \right] + \left[\frac{X_m + X_r}{wr_r} \right] \cdot \left[\frac{(r_s + R_e) + j(X_e + X')}{R_e + jX_e} \right] \frac{dE_t}{dt} = 0 \tag{20}$$

Which can be written as

$$E_t \cdot \left[\frac{wr_r}{(X_e + X_r)} \left[\frac{r_s + R_e + j(X_e + X_s + X_m)}{r_s + R_e + j(X_e + X')} \right] \right] + \frac{dE_t}{dt} = 0 \; , \tag{21}$$

where equation (21) can be expressed in the familiar differential equation for[46] as

$$E_t\gamma + \frac{dE_t}{dt} = 0, \qquad (22)$$

where $\gamma = \alpha + j\beta$. To determine α and β, the following substitutions are made and the real and imaginary components are separated:

define $r_s + R_e = R_1,$

$X_e + X_s + X_m = X_1,$ and

$X_e + X' = X_2.$

Substituting these values into the above equation yields:

$$\left[\frac{wr_r}{X_m+X_r} \cdot \frac{R_1+jX_1}{R_1+jX_2}\right] \cdot \left[\frac{R_1-jX_1}{R_1-jX_2}\right] = \frac{R_1^2+X_1X_2+j(R_1X_1-R_1X_2)}{R_1^2+X_2^{\,2}},$$

$$\alpha = \left[\frac{wr_r}{X_m+X_r}\right] \cdot \left[\frac{R_1^2+X_1X_2}{R_1^2+X_2^2}\right].$$

Resubstituting for R_1, X_1, and X_2 yields

$$\alpha = \frac{wr_r}{X_m+X_r} \cdot \left[\frac{(r_s+R_e)^2+(X_e+X_m+X_s)(X_e+X')}{(r_s+R_e)^2+(X_e+X')^2}\right] \qquad (23)$$

and,

$$\beta = \frac{wr_r}{(X_m+X_r)}\left[\frac{R_1X_1-R_1X_2}{R_1^2+X_2^2}\right]$$

$$\beta = \left[\frac{(r_s+R_e)\ (X_e+X_s+X_m)-(X_e+X')}{(r_s+R_e)^2+(X_e+X')^2}\right]\cdot\left[\frac{wr_r}{(X_m+X_r)}\right]$$

which reduces to

$$= \left[\frac{(r_s+R_e)(X_s-X'+X_m)}{(r_s+R_e)^2+(X_e+X')^2}\right]\cdot\left[\frac{wr_r}{(X_m+X_r)}\right] . \qquad (24)$$

The solution to the differential equation (22) is

$$E = E_i e^{-\gamma t} \quad , \qquad (25)$$

which can be rewritten as

$$E = E_i e^{-\alpha t} e^{-j\beta t} \qquad (26)$$

where E_i is given by the initial conditions $e'(t=0)= e'_i$, where e'_i is the terminal voltage of the generator immediately prior to the isolation of the generator and its associated protion of the distribution feeder from the rest of the power system. Therefore,

$$e'_i = E_t = I_s(r_s + jX')\Big|_{t=0^-} \tag{27}$$

$$e'(t=0^+) = E_i\left[\frac{r_s+R_e+j(X_e+X')}{R_e+jX_e}\right] = e'_i \;. \tag{28}$$

Therefore,

$$E_i = e'_i\left[\frac{j(R_e+jX_e)}{r_s+R_e+j(X_e+X')}\right].$$

Whether the voltage increases or decreases is determined by the first term in equation (26), $e^{-\alpha t}$. If is positive, the voltage will decay. If α is negative, the voltage will increase. Whether α is positive or negative can be determined by examining equation (23):

$$\alpha = \frac{wr_r}{(X_m+X_r)}\cdot\left[\frac{(r_s+R_e)^2+(X_e+X_s+X_m)(X_e+X')}{(r_s+R_e)^2+(X_e+X')^2}\right].$$

The only characteristic which can realistically be negative is X_e, the equivalent system reactance. With this in mind, further analysis reveals that the sign of α will be determined by

$$(r_s+R_e)^2+(X_e+X_s+X_m)(X_e+X') \quad , \tag{23a}$$

since the term $(X_e+X')^2$ in the denominator will always result in a positive quantity. For to be negative, all three of the following conditions must be satisfied:

$$\left|(r_s+R_e)^2\right| < \left|(X_e+X_s+X_m)(X_e+X')\right| \tag{29a}$$

$$X_e < 0 \tag{29b}$$

$$\left[X_m+X_s\right] < \left|X_e\right| < \left[(X_s+X_m // X_r)\right] . \tag{29c}$$

If the conditions in equations (29a), (29b), and (29c) are satisified, the terminal voltage will not increase indefinitely, as defined by equation (26). In actuality, the magnetizing reactance, X_m, will decrease as the voltage increases until finally reaching a value where $(r_s+R_e)^2=(X_e+X_s+X_m)(X_e+X')$. Consequently, α will go to zero, resulting in a constant terminal voltage.[47]

Care must be taken when utilzing equation (23) to investigate for possible self excitation. The R_e and X_e terms represent the equivalent system load and reactance as a series impedance. The capacitors connected on the line are in parallel with the feeder load. This parallel combination must be converted into a series equivalent for use in equation (23). This elementary transformation is shown in Appendix II.

The effect of this increase in terminal voltage of the generator on the wave shape of the load current is dependent mainly upon the magnetic core characteristics of the system transformers connected to this self-excited generator, although the ferroresonant characteristics of the generator core may also have some influence on the wave shape. In order to learn which harmonics and their respective magnitudes will be present for this condition, a specific installation will be analyzed.

The installation which will be examined for potential self excitation is the Middle Creek Hydroelectric Cogenerator connected to the Penns 23-1 12.47 kv line of the Pennsylvania Power and Light Comapny (PP&L). This installation consists of a single 350kw, 3-phase, 2400 volt, 60 hz, 1200 rpm induction generator with a full load efficiency of 94.5%. PP&L has performed extensive tests on distribution transformers typical of their system to obtain an accurate representation of the transformers' excitation characteristics. A one line diagram showing the distribution feeder, generator location, capacitor installations, and automatic sectionalizing devices is shown below in FIG. (4).

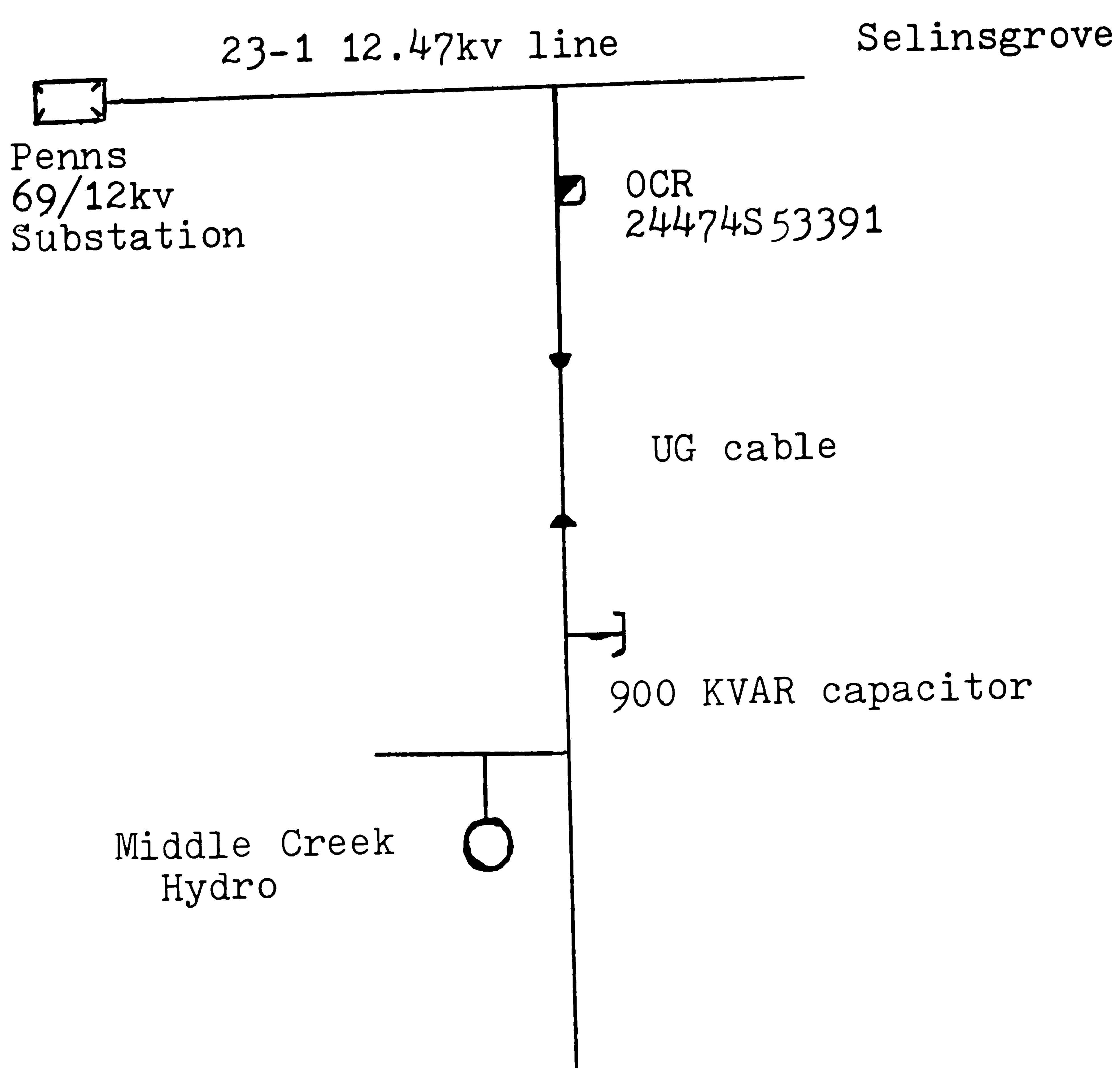


FIG. (4)

The biggest problem in examining for potential self excitation of induction generators is determining the equivalent values of r_r, X_r, X_s, r_s, and X_m of the respective generator from the information supplied by the manufacturer. For this specific installation, the manufacturer supplied the efficiency, power factor and line currents for half, three-quarters, and full load conditions, the no load power factor, full load RPM, and no load saturation curve. This information can be found in Appendix I.

The characteristic value easiest to determine form the manufacturer's data is the magnetizing reactance X_m. This value can be found by going to the no load saturation curve and reading the line current at rated voltage. For this particular machine, rated voltage at no load results in a current of 36 amperes. For this particular condition the power factor is given as 4.9. This yields an active core loss current given by :

$$I_{or} = 0.049 \times 36 = 1.76 \text{ amps} \quad . \tag{30}$$

This gives a core loss shunt resistance of

$$R_o = \frac{V_{tL-L}}{3^{1/2} I_{or}} = \frac{2400}{3^{1/2}\ 1.76} = 787.3\,\Omega\,. \qquad (31)$$

The reactance magnetizing current is found by

$$I_m = 36 \times \sin(\cos^{-1} 0.049)$$

$$= 36 \times \sin(87.19^{\circ}) = 35.96\text{A}\,. \qquad (32)$$

The magnetizing impedance is given by

$$X_m = \frac{V_{tL-L}}{3^{1/2}\ 35.96} = j38.53\,\Omega, \qquad (33)$$

and the overall effective impedance of R_{or} and X_m is

$$\frac{jR_{or}X_m}{R_{or} + jX_m} = \frac{j(787.3)(38.53)}{(787.3 + j38.53)}, \qquad (34)$$

which reduces to

$$\frac{j30334.67}{787.53+j38.53} = \frac{30334.67\,\angle 90^{\circ}}{788.23\,\angle 2.8^{\circ}} = 38.48\,\angle 87.2^{\circ}\,.$$

Had the no load saturation current been considered to be purely reactive (i.e., neglecting the R_{or} element of FIG. (2)), X_m would be determined by:

$$\frac{V_{tL-L}}{3^{1/2}\,36} = \frac{2400}{3^{1/2}\,36} = 38.49 \angle 90^\circ \,. \tag{35}$$

It is evident from comparing the values of equations (34) and (35) that the previous assumption that R_{or} can be neglected with little loss of accuracy is valid, and the model of FIG. (3) can be utilized for this particular machine.

Based on the efficiency for various load conditions, the value for the sum of r_s and r_r can be determined. The losses in the machine consist of I^2R losses in the stator and rotor, and relatively constant losses due to friction and windage. These losses can be expressed in the form of equation (36),

$$eI^2(r_s + r_r) + K = \text{total losses}, \tag{36}$$

where K is defined as the constant losses, expressed in watts, and the total losses found in equation (36) are also expressed in watts.

By solving equation (36) simultaneously for different load conditions, a value for the sum of r_r and r_s can be determined. Although each solution should produce the same value, it is possible that different solutions will produce different values, in which case an average should be taken. Substituting this average value into each of the equations for the different load conditions, an average value for the constant losses can be determined. Continuing with the data supplied for this particular machine in Appendix I, the loss equations for full, three-quarter and half load may be written as

$$\text{FULL LOAD: } 3(106.5)^2(r_s+r_r)+k = 20.370 \text{ watts} \qquad (36a)$$

$$\text{3/4 LOAD: } 3(83.2)^2(r_s+r_r)+k = 15.278 \text{ watts} \qquad (36b)$$

$$\text{1/2 LOAD: } 3(62.5)^2(r_s+r_r)+k = 11.567 \text{ watts} \qquad (36c)$$

Solving equations (36a) and (36b) simultaneously yields a value of 0.384 for the term (r_s+r_r). Solving equations (36b) and (36c) simultaneously yields a value of 0.410Ω for the term (r_s+r_r). The simultaneous solution of equations (36a) and (36b) yields a value of 0.395Ω. Averaging these three values together gives a value of 0.396Ω for (r_s+r_r).

A vector diagram, shown in FIG. (5), illustrating the relative quantities of an induction machine can now be utilized to extract the specific values for r_r and r_s, as well as the values for X_r and X_s.

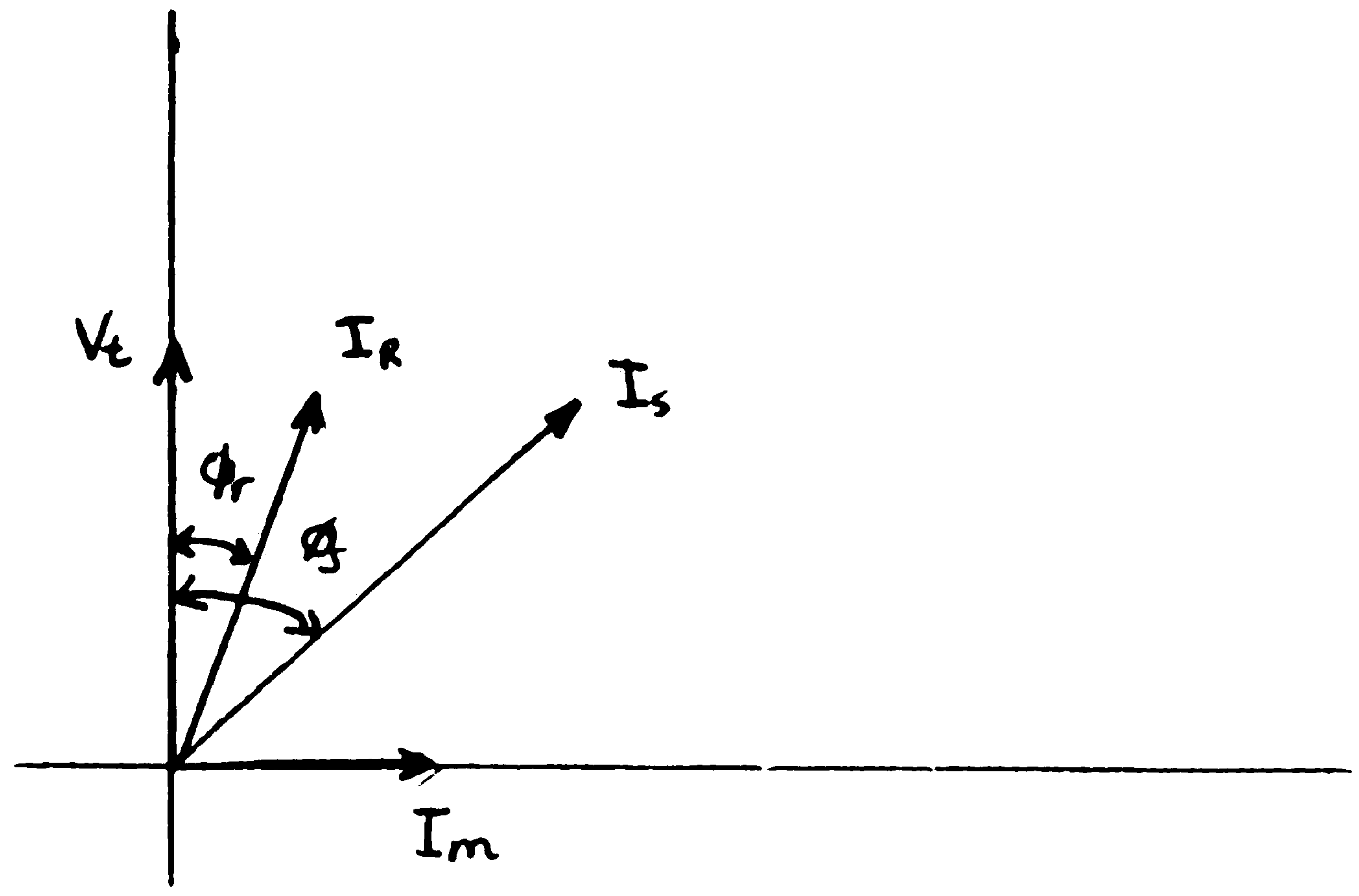


FIG. (5)

In the above diagram, I_m is drawn on the horizontal. In reality, this vector would be located in the first quadrant, lagging V_t by 87.2^{o} (0.049 pf). However, it was previously proven that disregarding the slight real component of this current introduces very insignificant error. Thus, the value of I_m is shown on the horizontal. From this vector diagram, the following relationships can be defined for the different load conditions.[49]

$$I_r \sin(\phi_r) + I_m = I_s \sin(\phi_s) , \qquad (37)$$

$$I_r \cos(\phi_r) = I_s \cos(\phi_s) . \qquad (38)$$

Examining these relations at full load yields

$$I_r \sin(\phi_r) + 36 = 106.5 \sin \cos^{-1}(0.837)$$

$$I_r \sin(\phi_r) = 22.28$$

$$I_r \cos(\phi_r) = (106.5)(0.837)$$

$$I_r \cos(\phi_r) = 89.14.$$

The magnitude of I_r is defined as

$$\left| I_r \right| = \left[(89.14)^2 + (22.28)^2 \right]^{1/2} = 91.88 \text{ amps} . \tag{39}$$

The angle ϕ is determined by

$$\phi_r = \tan^{-1} \frac{(22.28)}{(89.14)} = 14.04^{\circ}. \tag{40}$$

Now that I_r is known, the rotor resistance can be determined from the induction machine equation for mechanical power.[50]

$$\frac{(3I_r^2 \cdot r_r)}{s} = \frac{P}{(1 - s)} .$$

The only value which is not known for this equation is the slip, s. For this it will be necessary to make a reasonable approximation for slip based on the size of the machine. For machines of this relative size (350 kW, 1200 rpm) a typical value for full load slip is 1.67%. Substituting this value into equation (40) yields

$$\frac{(3)\cdot(91.88)^2\ r_r}{0.0167} = \frac{350{,}000}{0.9833}\ ,$$

solving for r_r yields

$$r_r = 0.235\,\Omega\ ,$$

since $(r_r + r_s) = 0.396\,\Omega$ (found by simultaneously solving equations (36a),(36b), and (36c)), r_s is equal to 0.396 - 0.235, or $0.161\,\Omega$. Utilizing the value of ϕ_r determined by equation (40) and the fact that $\tan(\phi_r) = (x_r + x_s)/(r_s + (r_r/s))$, the quantity $(X_r + X_s)$ can be found by substitution:

$$0.250 = \frac{(X_s+X_r)}{0.161 + \dfrac{0.235}{0.0167}}\ , \text{ or}$$

$$(X_s + X_r) = 3.558\,\Omega.$$

Once again, an approximation must be made to complete the analysis. For machines of this size, X_s is slightly greater than X_r, although not by an appreciable amount. Therefore, assuming that X_s is 53% of the sum of X_s and X_r yields:

$$X_s = 1.888\,\Omega$$
$$X_r = 1.674\,\Omega$$

The effects of the error due to this approximately 50% split assumption between X_s and X_r is minimal.[51]

A summary of the machine characteristics is listed below, given in ohms and in per unit on the machine base (418 KVA) and the power system base (10,000 KVA).

		PER UNIT	
	OHMS	418 KVA_B	10,000 KVA_B
X_m	j38.49	j2.793	j66.8182
X_s	j1.886	j0.137	j3.278
X_r	j1.672	j0.121	j2.894
r_r	0.235	0.017	0.4067
r_s	0.161	0.012	0.2871

Now that all of the necessary machine values have been determined it is possible to complete the analysis of the Middle Creek Hydroelectric Cogenerator for possible self excitation and overvoltage. In order for an induction generator to become self excited, there are certain conditions which must be met. First, the possibility that the generator may become isolated from the power system must exist. Since the PP&L 12kV system is operated radially, any condition which would cause the Oil Circuit Reclosure (OCR) at pole 24474853391 or the substation circuit breaker to operate would isolate the generator. Secondly, there must be sufficiently connected capacitance on the line to supply all of the necessary magnetizing VARs of the machine (X_s+Xm//X_r). Any value of capacitive reactance less than this would be unable to support self excitation. Finally, although there are mathematical equations to represent the interaction of the machine with the system for various load conditions, common sense dictates that the connected load to the generator upon isolation should be no greater than the rating of the generator, since the maximum available mechanical energy input is equal to the rating of the machine. It is highly doubtful that this installation could supply the entire load of this distribution feeder, hence the case of self excitation for operation of the station circuit breaker can be discounted. However, with the operation of the OCR at pole 24474S53391, the generator is not only isolated from the power system, but is also isolated from a significant portion of the feeder load (Susquehana University and part of the town of Selinsgrove). Late winter load samples taken in the early morning hours, usually a high demand period on non-industrial feeders of this type, on the portion of the feeder beyond the OCR, revealed a load of approximately 1100kw. Hence, it is very possible that during traditionally light load periods (mid-mornings and afternoons in late spring and early fall) the load on this portion of the feeder may approach 350 kw, the rating of the generator. This fact, combined with the existence of the underground cable on the feeder (UG cable has high capacitive characteristics) and the sizable capacitor support located near the machine (900 KVAR bank), make this installation a prime candidate for self excitation.

A good scenario to analyze for this installation is 900 KVAR connected capacitance (capacitance from the UG cable is neglected, although it must be remembered that this will compound any problem) and a feeder load of 350 kw (exactly matching that of the generator). This represents R_L = 28.57 pu and X_C = -11.11 pu (10,000 KVA base). Substituting these values in the transformation formulas of Appendix II yields an R_e of 3.753 pu and X_e of -9.6513 pu. Substituting these values, along with the pertinent machine equivalent values previously determined into equation (23a) yields a result of -201.142, which indicates that self excitation will occur for this condition. Once it has been determined that self excitation will occur, the next item which must be determined is the maximum value that the voltage will rise to. This is determined by finding when equation (23a) will go to zero. Although this could be found by rearranging terms and solving the basic quadratic equations, the solution can just as easily be found by trial and error with a programmable calculator. For this particular example, equation (23a) will go to zero for X_m approximately equal to 10.34 pu. On the machine base of 418 KVA this equates to 0.43 pu, or 5.96 Ω. Going along the machine saturation curve to the furthermost point yields an X_m of approximately 19Ω. At this point, the terminal voltage is approximately 2900 volts, almost 121% of the rated voltage, where this value is in fact not the final operating point of the machine as defined by equation (23a). The results of equation (23a) dictate that the terminal voltage will be greater, where the actual value is difficult to ascertain since the farthest point of the saturation curve has already been analyzed. The behavior of the saturation curve beyond this point is difficult to predict, although the curve will probably begin to approach a horizontal line. A rough extrapolation of the curve yields a horizontal asymptote of approximately 3000 volts, a 125% overexcitation.

Observation of the transformer saturation curve of FIG. (1) reveals that the linear range of operation extends to 1.10 pu excitation. Any excitation beyond this point will begin to produce distorted currents. At 120-125% of excitation, the transformer is well beyond its linear region of operation, and is into its saturated region.[52] Further tests conducted by PP&L on typical distribution transformers, with this magnitude of overexcitation (120%), produced voltage and current waveforms similar to those shown in FIG. (6).

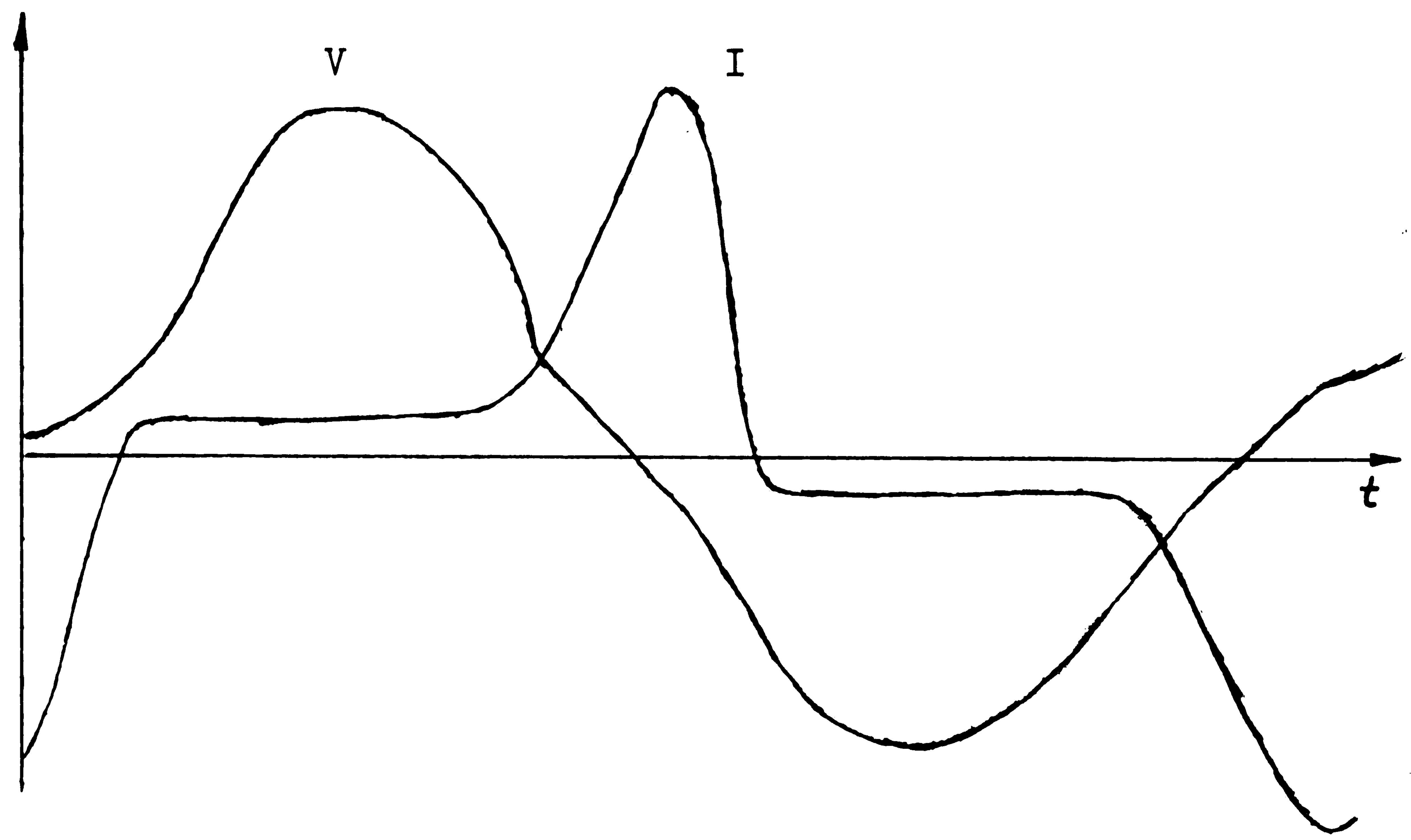


FIG. (6)

These waveforms were measured with a digital oscilloscope and recorded on floppy disks for computer analysis. The computer analysis of the voltage waveform revealed the presence of harmonics up to the 24th, with the most significant harmonics being the third (15% of the fundamental), fifth (8% of the fundamental), and ninth (3.5% of the fundamental). This computer analysis does not include any harmonics which may occur due to saturation within the generator or the existence of a ferroresonance condition, where these types of harmonics may only compound the problem.

CHAPTER 3

DEVELOPMENT OF A DETECTION SCHEME FOR EXCESSIVE HARMONICS PRODUCED BY SELF EXCITED INDUCTION GENERATORS

Standard protection for overvoltages of the magnitude associated with the Middle Creek Hydroelectric installation described in Chapter 2 consist of overvoltage relays set to operate at 105% of nominal voltage. Superficially, it appears as if the standard overvoltage relays will operate for this condition and prevent the infiltration of any harmonics which may be generated until the performance of these relays with distorted waveform inputs is analyzed. Tests conducted on voltage relays with distorted waveforms for excitation reveal an increase in operating time as well as an increase in the relay pick-up value, where this increase is found to be as much as 25%, even for relatively low levels of distortion.[53] Hence, there is no guarantee that the overvoltage relays will operate for this condition, and, therefore, a need exists for some type of protection which will be more reliable than the overvoltage relays in detecting overvoltages in distorted waveforms.

One alternative to the detection of these harmonics is possibly the prevention of self excitation. This is not always possible as is evident in this case, since the one thing which would prevent self excitation, removal of the line capacitors, is not feasible sicne the capacitors are required for voltage support on the line during normal operating conditions. Another solution would be to install a direct transfer trip link between the OCR and the customer's point of contact (POC) CB. This link includes a communication channel (optical fiber, hard wire, microwave, etc.), a transmitter at the OCR to transmit whenever the OCR trips, and a receiver at the customer;s POC. These types of schemes are very expensive, costing two to three times as much as this cogenerator installation. Thus, this condition is not preventable and some form of protection is required.

The first links in detecting harmonics on the power system are the voltage and current transducers. In order to accurately detect harmonics on the power system it is first necessary to obtain a signal which is an accurate representation of the waveform on the power system at levels suitable for the detecting device. Ideally, the transducers should not distort the signal in any way. In reality, the object is to keep this distortion to a minimum. The main types of transducers used to obtain representative signals of system currents and voltages are current transformers and potential transformers.

Results from tests on commercially available CTs indicate that frequencies up to 20kHz were transformed with less than 3% error, for loads less than 10Ω.[54] Tests conducted on commercially available PTs reveal that their frequency response is a function of the connected burden. For burdens of 10^3 ohms or more, the PTs were found to be able to reproduce signals up to 10kHz with less than 3% error. For burdens of 10^2 ohms, the frequency response (of 3% maximum error) dropped to anywhere from 1kHz to 6kHz, depending upon the voltage rating of the PTs.[55] From these results, it is observed that CTs can be expected to accurately reproduce most any signal which may appear on the power system (20kHz is well beyond the 300^{th} harmonic). However, caution must be exercised if PTs are to be utilized (1kHz=15^{th} harmonic). If PTs are going to supply the excitation for any harmonic detecting device, it should be determined that the device's burden is such that the PT will accurately transform the frequencies that are to be detected (especially of those harmonics to be monitored are above the 15^{th} harmonic).

Now that the frequency response of the transducers has been determined, the requirements for the detecting device can be developed. First and foremost, the device should be capable of handling the frequencies which it is required to detect. This demands either some knowledge of the frequencies expected for a particular installation, or the use of a device with a cut off frequency well above any expected harmonic frequency. The more practical approach would be to design the cut off frequency to be as high as possible, allowing one standard device to be used at many different installations. For example, the particular installation under study only exhibits frequencies up to the 24^{th} harmonic, but other installations are known to exhibit frequencies up to the 50^{th} harmonic. Another area of concern is the shape of the response curve. The response should be relatively flat throughout the range of expected frequencies since it is very undesirable for the device to be activated simply because it was exposed to one frequency at which it was more sensitive than other frequencies. Another factor, which is associated with transducer frequency response, is device burden. If the device is going to be durrent-excited, its burden should be as low as possible (at least less than 10Ω). If potential excitation is to be utilized, the burden should be as high as possible (at least 10^3Ω). The development of this detection device should also consider the use of an adjustable trip setting, allowing for maximum versatility. While one location may be subject to 25% harmonic distortion, others may be subject to less. Hence, if the device is designed to trip at only one, permanent level, its usefulness is limited and it may not operate properly at other locations. One final factor, which may be the most significant, is cost. In considering the cost, the purpose of the detection device must be kept in mind, where for this particular case, the detection device is being used to prevent a small (350kw) induction generator from producing harmonics on a 12kV distribution feeder. Although the harmonics are undesirable, the cost-benefit ratio of the device must be considered. Obviously, the consequences of harmonics produced by this installation are minimal and are not of as great a concern as those from 4,000 hp SCR-controlled DC motor on the 69kV system. As a result, an electric utility would be willing to spend more money to assure prevention of pollution form the SCR-controlled motor than from a small generator. In summary, the factors to be considered in designing the harmonic detection device include:

1) capable of operation over large bandwidth,
2) device burden
   a) low burden for CTs,
   b) high burden for PTs,
3) adjustable trip setting, and
4) cost.

Now that the requirements for the harmonic detection device have been established, different methods which may be used to accomplish this objective can be explored. With the current proliferation of minicomputers and microprocessors, the first method of detecting harmonics which comes to mind is one which utilizes some type of digital computational system. Ideally, it would seem as if this type of detection system would satisfy all of the given technical constraints. In particular, the bandwidth of a given minicomputer or microprocessor is limited only by its sampling rate and associated software. Additionally, the burden of the device can easily be controlled and the "trip settings" can be adjusted in the device software. The use of microprocessors in protective relaying is not a new idea, as there are many protective relay schemes for transmission lines commercially available which itilize microprocessors. However, detecting harmonics cannot be compared to detecting transmission line faults.

There presently exist spectrum analyzers which are capable of digitally analyzing a given signal for frequencies as high as the 60^{th} harmonic by using well-known fast Fourier transform (FFT) algorithms. These analyzers, however, either require a magnetic disk recording of the signal being analyzed or a memory which stores a predetermined number of samples of an on line signal. Once the samples have been processed, they are erased from memory and a new set of samples are obtained. Hence, the on line technique does not monitor all of the signal. The reason for this is obvious when the necessary sample rate and process time are reviewed. To accurately evaluate the 60^{th} harmonic (3600 hz) requires a sampling rate of 7200 hz, as defined by the Nyquist criteria. A sampling rate of 7200 hz allows the processor approximately 138 microseconds to completely analyze the preceding 3600 samples, if the signal is to be continuously monitored. Even if the desired upper frequency were decreased to 900 hz, detection would still require a sampling rate of 1800 hz, limiting the processor to 550 microseconds between samples to analyze 1800 samples. The speed of today's processors does not allow a complete analysis of such a large number of samples in such a short period of time. A viable alternative used by state of the art real time spectrum analyzers is to alternately sample and process for selected periods of time as previously described. Once this information has been processed, and the harmonic spectrum obtained, adding additional software to check for excessive harmonic content (and produce some sort of control signal) should not be that difficult. The biggest drawback to schemes similar to this is cost. The spectrum analyzers presently available cost thousands of dollars, even before the comparison software and logic necessary to produce an external signal for excessive conditions is added.

Another potential drawback to use of solid state processing devices is operation within a hostile environment. These analyzers function well in a laboratory setting, but the effects of high amounts of RF and other electromagnetic fileds (often present at substations) on the processing device have not yet been fully examined. Clearly, the ideal solution would be to have the samples transmitted from the substation to the remotely located detection device, where a means must also exist to send a control signal back to the substation. The development of optical fiber technology may not only make this possible, but may also help solve the other major problem, cost. A central processor utilizing a fiber optic communication channel may be able to monitor several installations. Although each installation would not be monitored continuously, instead sharing processor time with other installations, each installation would still be evaluated on a regular basis, for example, every two or three seconds. This evaluation should be frequent enough to allow prompt detection of harmonics at a particular site, while "sharing" the high costs of the processor with other installations.

Although the above solution may be economical for many large industrial customers, it is not viable for installations with small inductive generators, such as Middle Creek Hydro. A more economical and reliable method for detecting harmonics in this case those produced by an overexcited generator) is still required. Additionally, in light of the above discussion, it can be concluded that any method of excessive harmonic detection in these smaller installations will have to be accomplished in the analog mode to be economical. When using an analog harmonic detection scheme, care must be taken to assure that the analog circuitry does not introduce any significant distortion into the signal. Ideally, all non-60 hz frequency components should be separated from the fundamental frequency to provide accurate harmonic detection. The level of the non-60 hz frequencies should then be compared to determine if an excessive harmonic condition exists. The method utilized to provide this frequency separation and comparison will thus determine the accuracy and reliability of the scheme, much the same way that the sampling rate and software determine the accuracy of a digital detection scheme.

Separating out the non-60 hz portion of the signal is not difficult and can easily be obtained by known filtering techniques. In particular, filters can be designed which will separate the various expected harmonics from the 60 hz signal. This requires some knowledge of which harmonics will be present. In order to make the device more versatile, a variable filter network could be formed using variable capacitors. A more difficult problem associated with an analog harmonic detection scheme is providing a method of determining when an excessive harmonic condition exists, which requires that the magnitude of non-60 hz signal present be compared against a predetermined reference value. If the magnitude of the non-60 hz frequency components is found to be greater than the reference level, there must be some way to initiate tripping of the interconnecting circuit breaker.

To determine if an excessive harmonic condition exists, the outputs from these filters could be compared against a reference voltage. However, a problem arises in the comparison of these two quantities when it is remembered that the quantities being compared are both AC signals, and that any phase angle difference between the two voltages could result in a "desensitized" device. The ideal solution would be to compare DC quantities. This can be accomplished by placing a full wave rectifier immediately following each filter. The DC level at the output of the rectifiers should be an accurate representation of the level of the particular harmonic present. To achieve a "smooth" DC output, filter capacitors could be added to the rectifier. The affect on the overall frequency response attributed to the addition of the rectifier and capacitors is minimal.

A block diagram of the system developed is shown below in FIG. (7):

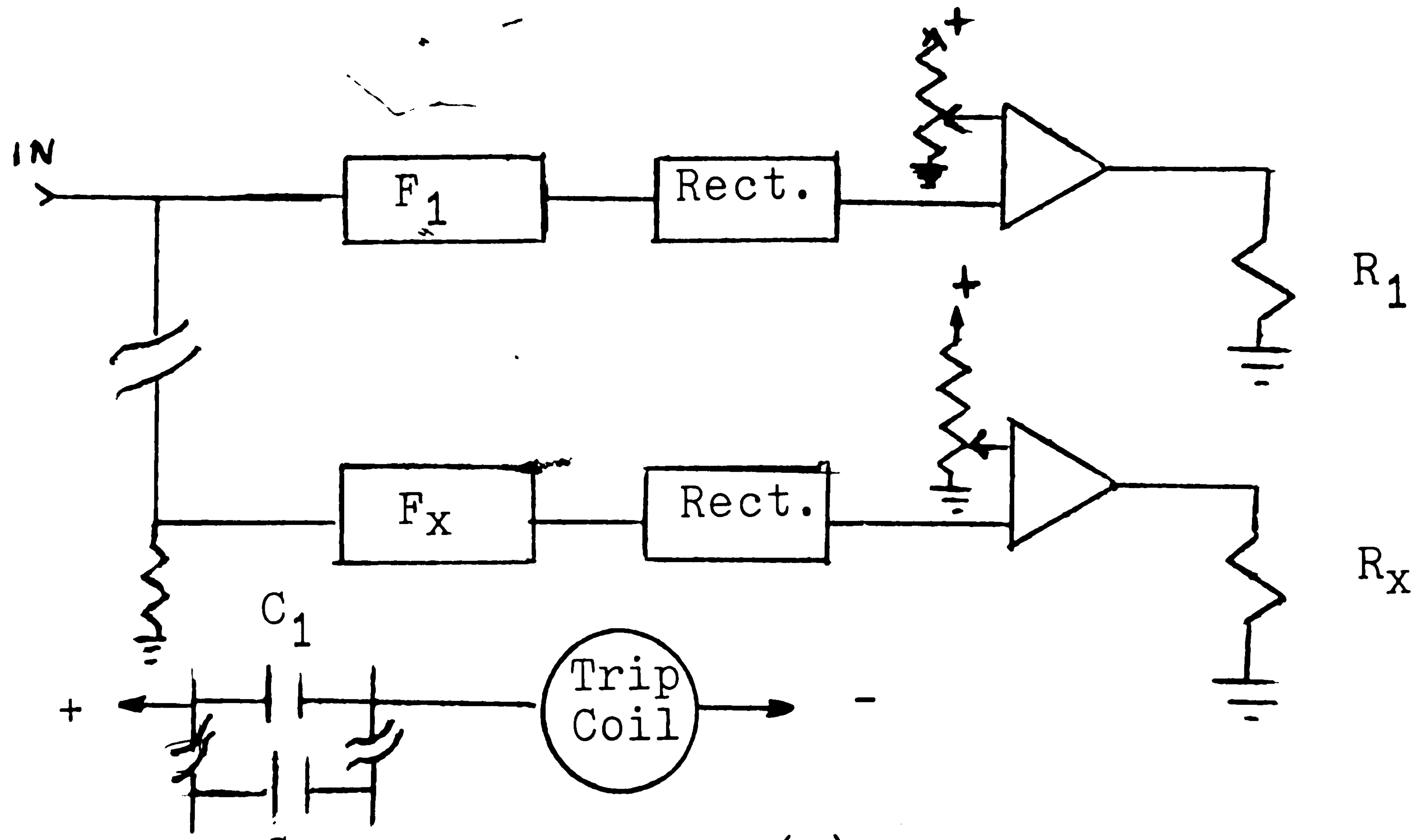


FIG. (7)

where F denotes a bandpass filter at a predetermined frequency f_x, R_x denotes a relay coil, and C_x denotes a relay contact. The reference voltage applied to the comparator can be a predetermined DC voltage obtained by a constant voltage source and a rheostat, as shown in FIG. (7). Use of a rheostat and voltage source make the device more versatile by allowing different "set" levels. The initiation to trip the circuit breaker is accomplished by the output of the comparators. Whenever the input to a comparator exceeds the set level of the reference voltage, the output changes state, that is, a voltage is produced at the output. When a coil of a relay is placed between the output and ground, a current will flow through the coil causing its contact to change state, where this change in state could initiate tripping in the breaker control circuitry.

Although the system just described should, in the ideal case, function to detect the different harmonics it is still quite cumbersome from a circuit point of view. First, the different reference levels for each individual frequency must be calculated and set. Although this method allows for flexibility, it would be quite time consuming to calculate each individual setting. It would be advantageous if one reference setting could be utilized for all frequencies. Further, it would be preferable to compare these DC representations against a percentage of the DC portion of the fundamental frequency, rather than using a comparison against a calculated quantity. For example, the comparator could be set to operate if the DC voltage of the harmonic is greater than some arbitrary percentage of the entire DC voltage of the fundamental. This percentage of the fundamental DC voltage can be obtained by a potentiometer functioning as a voltage divider.

Comparing against a percentage of the fundamental eliminates the need to try and calculate the DC voltages the excessive harmonics may produce at the output of the rectifiers in the device. By adding a filter, rectifier, and variable resistor for 60 hz, this percentage reference quantity can be obtained. A block diagram of the revised system is shown below in FIG. (8):

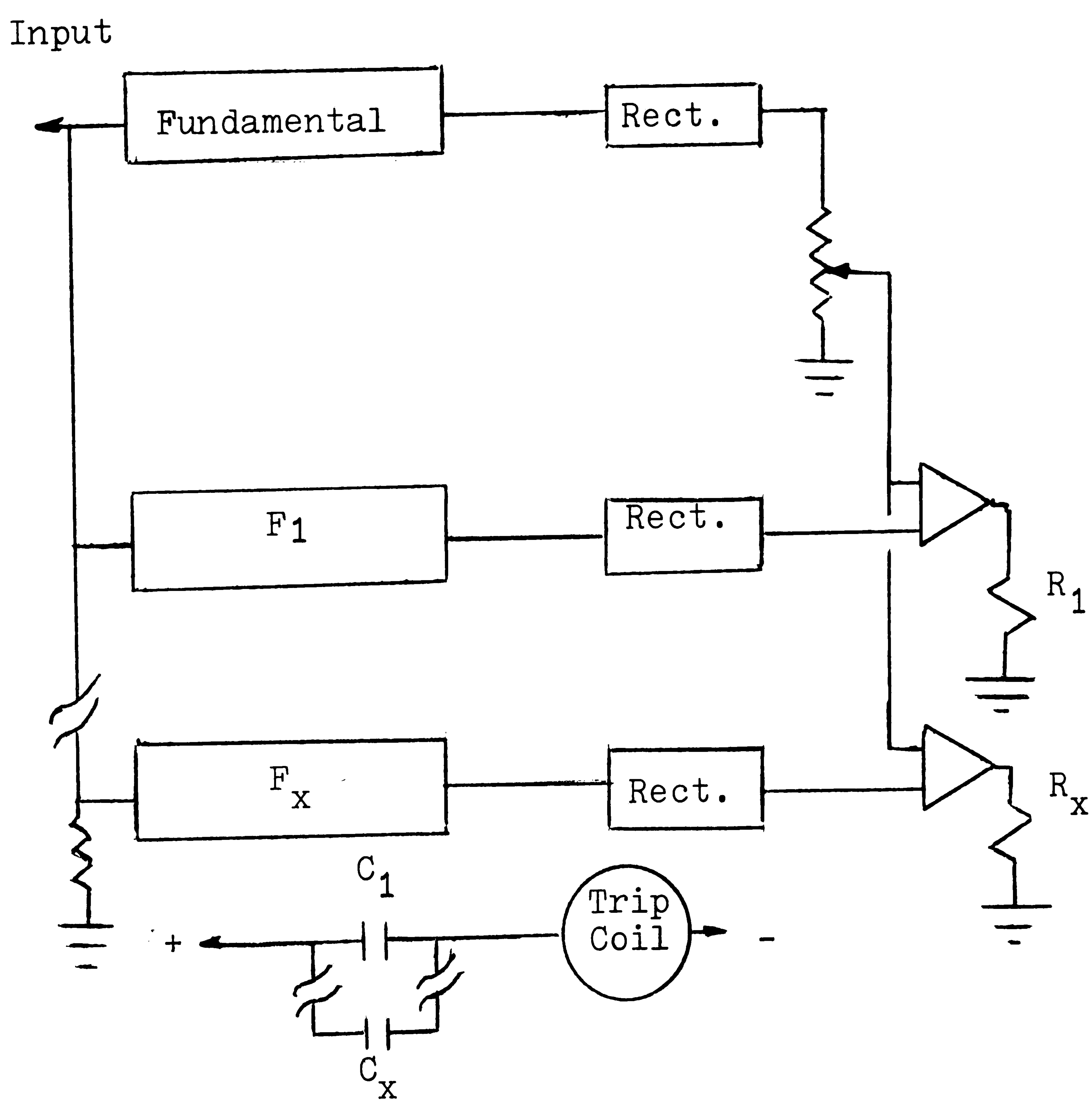


FIG. (8)

Although it appears as if the scheme developed should adequately function in the detection of harmonics, there are still some aspects which could be improved. A first aspect to be considered concerns the situation when the magnitude of each individual harmonic is not great enough to warrant an operation of the device, but the sum total of the magnitudes is large enough so that the device should be activated. In the scheme discussed above, it would not be possible for this condition to be detected. Therefore, it would be desirable to be able to compare the magnitude of the combined harmonic components against the fundamental frequency. Another portion of the scheme which would be desirable to improve is with respect to the input filtering. In order to maintain flexibility, it is desired to keep all of the filters variable in operation. This variability creates a problem in that each variable filter used must be tuned during installation. To obtain maximum reliability, many filters may be required to monitor all of the possible significant harmonic frequencies. In addition, the dissipating resistor, required for frequencies which are not being monitored, may affect the response of the filters.

In summary, what is desired is a scheme which minimizes the number of filters, yet maximizes the number of harmonics monitored while capable of comparing the sum of the magnitudes of all of the monitored non-60 hz frequencies against the fundamental frequency. This is not as formidable a task as it appears. The purpose of the fundamental frequency bandpass filter in FIG. (8) is to separate out the 60 hz component of the signal. Once this is accomplished it follows that any remaining portion of the signal must consist entirely of non-60 hz frequencies. Therefore, all of the remaining harmonic bandpass filters can be eliminated and this remaining portion of the signal can be considered to be representative of all of the harmonics present. Once this signal is rectified, the resulting DC quantity can be considered to be an accurate indication of the sum of all of the non-60 hz frequency components.

By reducing the total number of filters required to two, not only is the complexity of the device reduced, but the flexibility of the design is likewise increased. Instead of requiring bandpass filters for the fundamental frequency and all of the harmonics, the only thing which is required is a method to separate the 60 hz signal from the remainder of the frequency spectrum which is present. A particular method of achieving this, which has proven to be quite satisfactory in harmonic measuring equipment, is the use of a 60 hz notch filter.[56] Incorporating this notch filter into the scheme shown in FIG. (8) results in the arrangement shown below in FIG. (9):

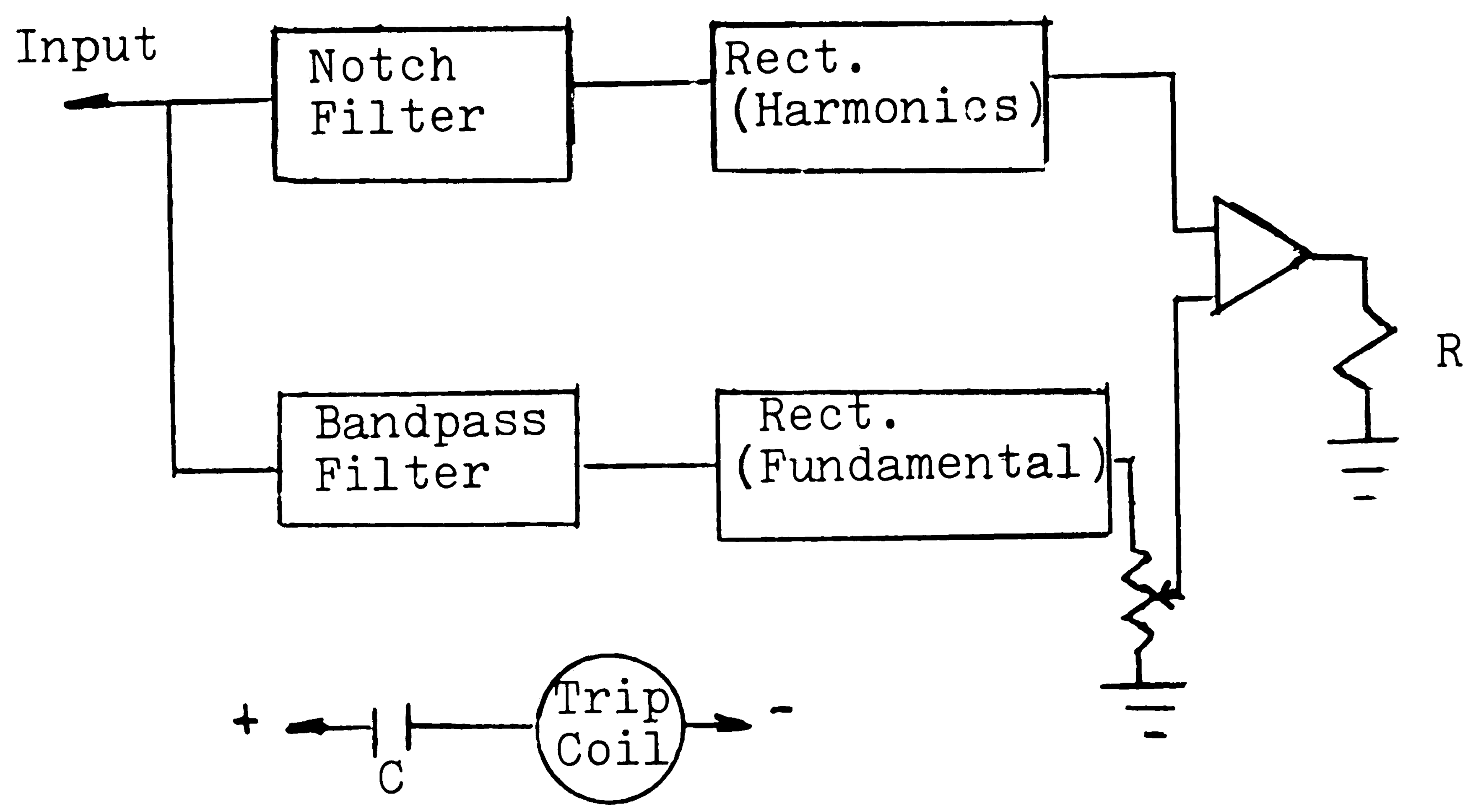


FIG. (9)

The scheme shown in FIG. (9) should adequately function to detect excessive harmonics on the power system produced by over excited generators. This particular arrangement is fairly simple, requiring only three adjustments, the tuning of the filters and the setting level for the comparator. The setting level is adjustable to produce a "detect" output signal anywhere in the range from the slightest presence of harmonics to harmonics equal in magnitude with the fundamental. This is accomplished by the variable resistor which controls the reference voltage to the input of the comparator. The upper frequency cutoff is limited only by the system transducers. The burden this detection device presents to the system transducers can be controlled by impedance matching transformers, if necessary. The circuit elements required to accomplish the functions in the block diagram are relatively inexpensive, including only a few resistors and capacitors for each filter, perhaps some operational amplifiers to provide a buffered output, two full wave rectifiers and filter capacitors, a comparator, and a relay. Additional amplifiers may be utilized to change the signal level from the transducer output to a value which is more suited for the comparator, where these additional components would not add significantly to the cost.

Although the system shown in FIG. (9) appears to be ideal for detecting harmonics, there remain some areas in which its performance is lacking. For example, if the device is activated, there is no way of knowing which particular frequency, or frequencies, was detected. With the digital scheme, as well as the previous analog scheme, this information is readily available and could be recorded in some manner for later reference. This information may be required for other sources of harmonics, but not for cogenerators, hence, it is not of great concern. Another drawback is frequency drift in the tuning of the notch filter, which may result from resistance changes as a function of temperature or drifts in any active device associated with the filter, may result in faulty operation Although this problem may also occur in the eariler versions of the analog scheme, any digital type of scheme would be immune to this problem, since all of the frequency analysis is accomplished in software, not circuitry. However, this problem is not as critical in this scheme as it would first appear. The finite width of the notch filter and the roll-off characteristics will include more than just 60 hz to begin with. Thus, if the tuning does drift, the 60 hz signal will not be entirely removed.

CHAPTER FOUR

A COMPUTER SIMULATION OF THE CHOSEN SCHEME

To evaluate the feasibility of the proposed scheme it will be simulated on a digital computer so that the performance of the scheme can be accurately predicted. The scheme can be simulated by modeling the frequency responses of the associated notch and bandpass filters, and comparing the respective outputs from the filters. The rectifier circuits need not be simulated since their characteristics are essentially independent of frequency.

Before the simulation can be performed, the structure of a 60 hz bandpass circuit must be derived. The transfer function for a typical bandpass filter is given by:

$$\frac{v_o(s)}{v_i(s)} = \frac{Ks}{s^2 + Bs + w_o^2} \quad . \tag{42}$$

One circuit which exhibits this function is shown below in FIG. (10):[57]

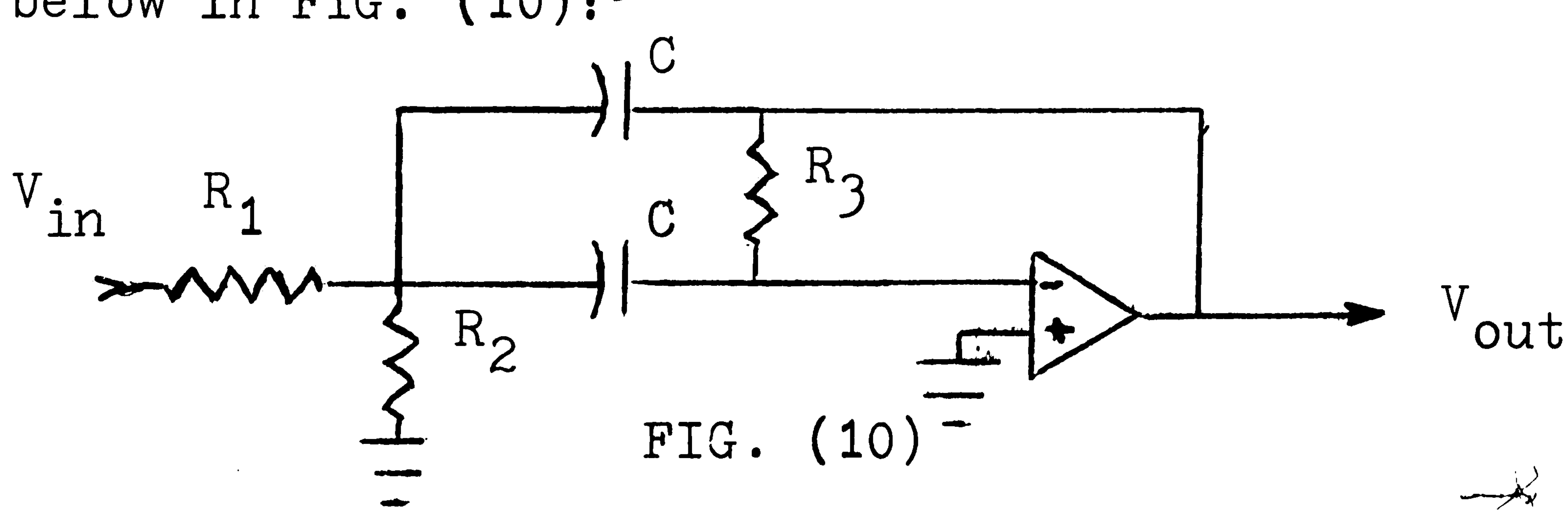


FIG. (10)

For this circuit, the constants of equation (42) are defined as:

$B = 2/R_3C$

$w_o^2 = 1/R_3C^2 \cdot (1/R_1 + 1/R_2)$

$Q = w_o/B$, and

$K = -1/R_1C$ (the 180^o phase shift can be ignored since the output goes to a full wave rectifier).

Maximum gain $= R_3/2R_1$.

For the bandpass filter, it is desired to have a fair amount of gain (e.g., 10) and a reasonably high Q (e.g., 10) to prevent passage of non-fundamental frequencies. Utilizing the above criteria and desired parameters, the following standard element values are obtained: R_1=56kΩ, R_2=2.7kΩ, R_3=1.2MΩ, and C=0.047μf. The actual center frequency, using the above equation and necessary conversion, is slightly greater than 60 hz, since standard element values were chosen. It should be noted that R_3 and C could both be made continuously adjustable, if need be, for critical applications.

Next, a 60 hz notch filter circuit must be developed. The transfer function for a typical notch filter is given by:

$$\frac{v_o(s)}{v_i(s)} = \frac{K(s^2 + w_o^2)}{(s^2 + Bs + w_o^2)} \quad . \qquad (43)$$

Shown below is a typical notch filter circuit.[58]

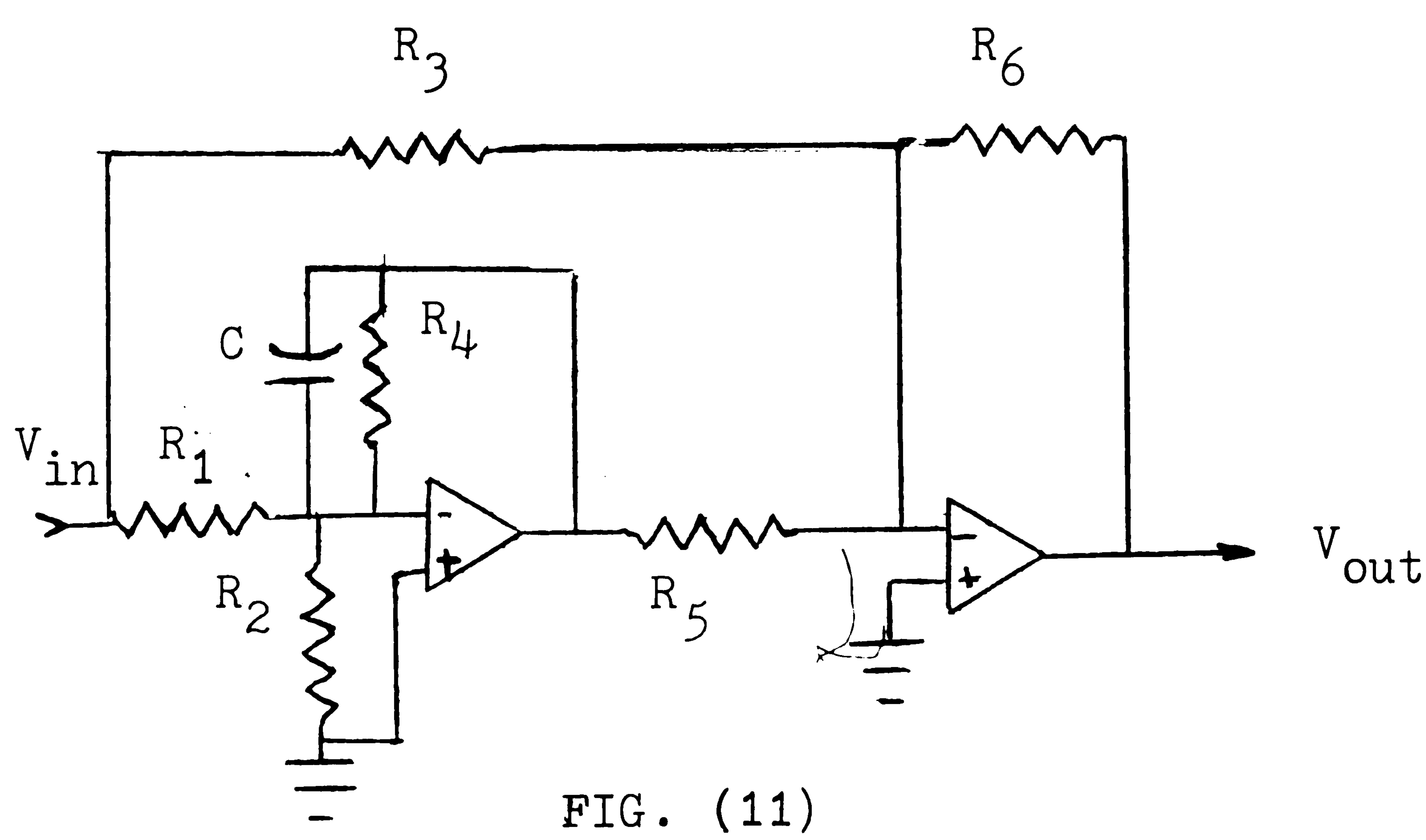


FIG. (11)

Provided the relationship $R_4R_3=2R_1R_5$ is maintained, the transfer function parameters are defined by:

$K = R_6/R_3$, which is the maximum gain,

$B = 2/R_4C$, and

$w_o^2 = 1/R_4C^2 \cdot (1/R_1 + 1/R_2)$.

It is desired to have the characteristics of this notch filter match, as close as possible, those of the bandpass filter (Q=10, gain=10). Based on these desired parameters and relationships, the following standard element values are derived, $R_1=270k\Omega$, $R_2=2.7k\Omega$, $R_3=34k\Omega$, $R_4=1.2M\Omega$, $R_6=340k\Omega$, and $C=0.047\mu f$. The relationship $R_3R_4=2R_1R_5$ dictates that $R_5=75.7k\Omega$. In reality, resistor R_5 could be made continuously adjustable to ensure proper circuit operation. With these element values, a center frequency of 59.8 hz is obtained.

To simulate this scheme, the frequency response of each filter is calculated utilizing values which are input by the user. The simulation then analyzes the response of the scheme to any desired waveform. This waveform must be represented by the magnitude of the 60 hz fundamental and all significant harmonic components. The magnitude for these frequency components may be entered in any of the following ways: (1) with the fundamental represented as unity and the harmonics as associated fractions of unity, (2) with the fundamental and harmonics entered as their respective fractional portions of the signal, or (3) as the calculated voltages (or currents) for each frequency component. For example, a signal which is composed of 75% fundamental and 25% third harmonic can be entered as:

(1) fundamental=1, harmonic=1/3; (2) fundamental=0.75, harmonic=0.25; or (3) fundamental=75V(A), harmonic= 25V(A). Since the device monitors the ratio between total harmonics and fundamental, the actual units used in association with the input quantities are not relevant.

A complete model of this proposed scheme using the component values defined above indicates that the scheme would be quite dependable for accurately detecting excessive harmonic conditions. A trial run, with a pure 60 hz signal input, revealed that fundamental leakage through the notch filter resulted in a ratio check of total harmonics to fundamental of less than 0.006 (0.6% error). Since a typical setting for this device would probably be 0.15 (total harmonic content approximately 13% of waveform), this device should operate properly for almost any possible excessive harmonic condition which may be produced by overexcited induction generators. In fact, for a trial run using only the three most significant harmonic components of the waveform illustrated in FIG. (6), the model predicted operation for a set point as high as 0.25.

The slightest overvoltage of an induction generator will start to generate harmonics in the output waveform. The proposed detection scheme is capable of accurately detecting harmonic levels on the order of 0.6%. This digital simulation clearly proves that this proposed method will adequately function to detect overvoltages from self-excited induction generators.

A copy of the computer program used to perform the simulation is on file in the office of the Electrical and Computer Science Department.

CHAPTER FIVE

CONCLUSIONS

Induction generators are often utilized on power systems by customers who have some type of renewable energy source (hydro, wind, bio-mas, etc.) available to supply energy to the generator. As mentioned before, these customers sell any excess power they produce to the utility. Induction generators are used as the electrical generating devices due to their simplicity and favorable price. Provided there is a suitable excitation source (usually the connected power system) the induction generators will produce electrical power of acceptable frequency and voltage.

When the induction generators become separated from their normal excitation source (the power system), their voltage will usually start to decrease due to lack of "excitation" or due to a connected load beyond its capability. At this point, undervoltage relays will operate to remove the generator from the system. In some cases, if there are a sufficient number of capacitors connected to the same line as the generator to supply the generator's excitation, the generator is said to be self-excited . If the remaining load is not beyond the capability of the machine, the generator may continue to generate acceptable quality electricity. However, if there is too much connected capacitance, the voltage at the output terminals will begin to increase (the generator is said to be over-excited) beyond acceptable limits. An analysis of the Middle Creek Hydro installation on the PP&L system indicates that this is a possible condition. At this point, the overvoltage relays should operate to isolate the generator from the system. However, often these overvoltages produce harmonics due to the magnetic characteristics of the distribution transformers connected to the system and possibly due to the saturation of the generator itself. Tests have shown that these harmonics greatly increase the operation time of the overvoltage relays, or prevent detection altogether. Because of this, there exists a need to be able to detect the harmonics which may be generated from the overexcited generators.

The method developed to detect these harmonics utilizies two DC voltages. One is obtained from the output of a full wave rectifier which is supplied from a 60 hz notch filter. The magnitude of this voltage is representative of the total harmonic content of the signal. The other voltage is obtained from the output of a full wave rectifier which is supplied only by the 60 hz fundamental frequency. The magnitude of this voltage is representative of the magnitude of the 60 hz funcamental. The scheme then compares the harmonic DC voltage against some predetermined fraction of the fundamental DC voltage. This predetermined value is the maximum permissible amount of total harmonic based on a percentage of fundamental frequency present in the signal. For example, if it is determined that the maximum amount of harmonics permitted on the system is 10% of the 60 hz component, 10% of the 60 hz DC voltage is the reference voltage. As long as the total harmonic content is less than this predetermined percentage of fundamental, in this case 10%, nothing happens. If the harmonic content is equal to or greater than this predetermined amount, the scheme will operate to isolate the machine from the system.

This scheme should function to adequately detect any excessive harmonics generated by an overexcited induction generator. A question remains, however, with regard to the acceptability of this same scheme to detect harmonics from other sources. The answer to this question depends upon what is to be detected. For example, if a steel mill is trying to detect a specific harmonic so that the respective available filter can be switched on, this scheme cannot be utilized since it is not capable of distinguishing between the different harmonics (although it could be easily modified to accomplish this, with additional cost and complexity). For this type of detection, some form of digital analysis may be desirable to differentiate the magnitudes of the different harmonics which are present. However, if an installation has some form of harmonic suppression equipment in service at all times, the protective device developed here may be used to detect faulted equipment. An example of this is an electronic AC/DC conversion station with harmonic cancellation transformers. As long as there are no faults within the transformers, and all other associated equipment is operating correctly, few harmonics, if any, will flow into the system. If a fault were to develop on one of the transformers, or if some equipment were to malfunction, harmonics would propagate into the system. In this case, operation of the detection device could serve as an early indicator that something was wrong.

The simplicity and relatively low cost of the proposed method makes it a desirable device to detect harmonics. However, no matter what their origin, it must be determined that the ability to differentiate between different harmonic components is not required for proper operation at a specific installation before this device can be used effectively.

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APPENDIX I

DATA FOR INDUCTION GENERATOR AT MIDDLE CREEK HYDROELECTRIC INSTALLATION

Nameplate data:

350kw, 1200rpm, 3-phase, 60 hz, 2400V

Test Data

	Full Load	3/4 Load	1/2 Load	No Load
Efficiency	94.5	94.5	93.8	-
Power Factor	83.7	80.3	71.8	4.9
Amps	106.5	83.2	62.5	-

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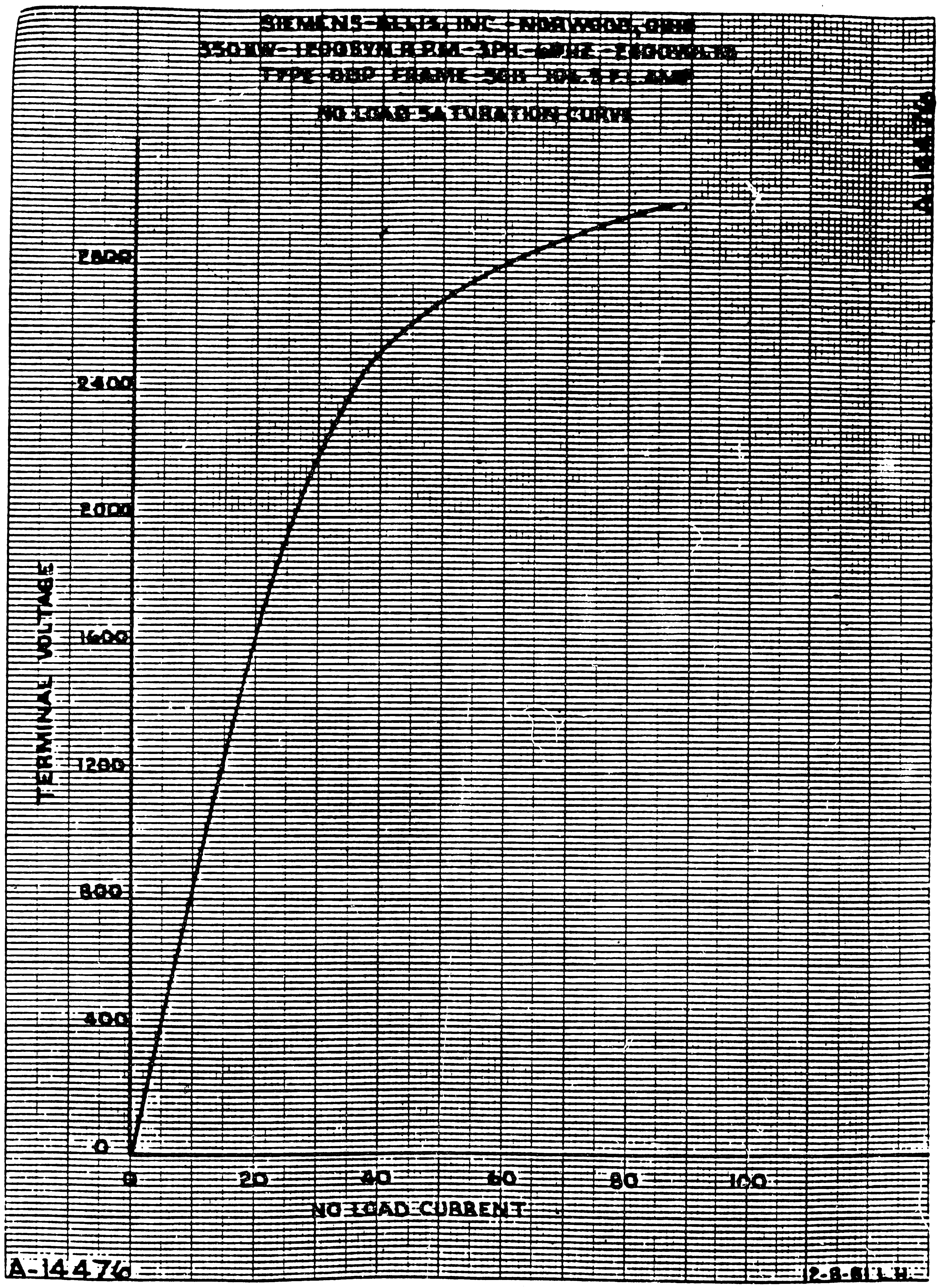
SIEMENS-ALLIS, INC - NORWOOD, OHIO
NO LOAD SATURATION CURVE
A-14476
TERMINAL VOLTAGE
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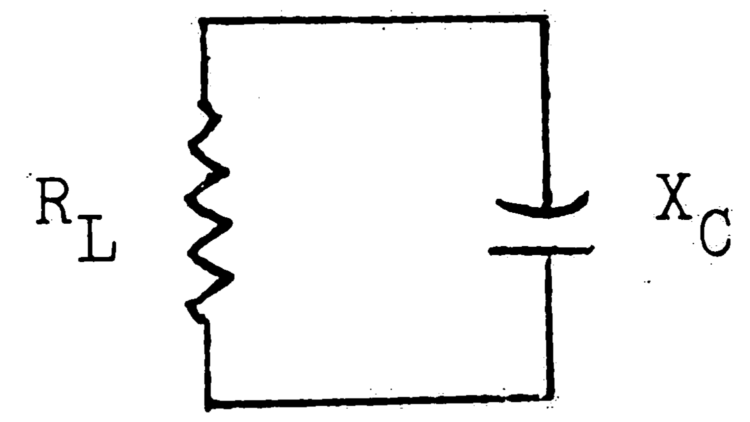
APPENDIX II

CONVERSION OF SYSTEM LOAD AND CAPACITANCE TO EQUIVALENT SERIES RESISTIVE AND REACTIVE COMPONENTS

The mathematical model of the generator utilized an external impedance of R_e+jX_e. The system load (R_L) and capacitance (X_C) are in parallel. Hence, the parallel combination of these system quantities must be converted to an impedance in the form of R_e+jX_e. This requires nothing more than finding the equivalent impedance of the parallel combination of R_L and X_C as shown below:



where

$$Z_{eq} = \frac{jR_LX_C}{R_L+jX_C} \quad . \qquad \text{(AII.1)}$$

Multiplying the expression of equation (AII.1) by its complex conjugate yields:

$$\frac{jR_LX_C}{R_L+jX_C} \cdot \left[\frac{R_L-jX_C}{R_L-jX_C}\right] = \frac{R_LX_C^2 + jR_L^2X_C}{R_L^2X_C^2} . \qquad \text{(AII.2)}$$

Separating the real and imaginary parts of equation (AII.2) results in:

$$R_e = \frac{R_LX_C^2}{R_L^2 + X_C^2} \text{, and} \qquad \text{(AII.3)}$$

$$X_e = \frac{R_L^2X_C}{R_L^2 + X_C^2} . \qquad \text{(AII.4)}$$

In the Middle Creek Hydro example of Chapter 2, the system load and connected capacitance were given as 350kw and 900KVAR, respectively. On a 10,000KVA base, these values can be represented as:

$$R_{L(pu)} = \frac{1}{\frac{350}{10,000}} = 28.57, \text{ and}$$

$$X_{C(pu)} = \frac{1}{\frac{900}{10,000}} = -11.111.$$

Substituting these values in the above equations (AII.3) and (AII.4) yields:

$$R_e = \frac{(28.57)\ (-11.111)^2}{(28.57)^2 + (-11.111)^2} = 3.753 \text{ pu, and}$$

$$X_e = \frac{(28.57)^2\ (-11.111)}{(28.57)^2 + (-11.111)^2} = -9.6513 \text{ pu.}$$

VITA

Paul Koba Jr. was born in Lansdale, PA on January 2, 1958, the oldest of two sons to Paul and Anne Koba. He attended North Penn High School in the vocational-technical curriculum, attending North Montco Area Vocational Technical School for half days, where he was enrolled in the Electronic Technology course. He graduated from both schools in June 1975. In September 1975 he enrolled at Lehigh University to study electrical engineering. He graduated with a BSEE in June 1979. After graduation, he accepted a job with Pennsylvania Power and Light Co. (PP&L) in the Construction Department as a cost and schedule analyst. In August 1981, he transferred to the Relay Section of the System Operating Department where he is presently employed. In 1983 he became a licensed Professional Engineer in the state of Pennsylvania. During his employment at PP&L he participated in the PP&L "in-house" MSEE program. This program permitted him to take time off from work (four hours per week) to attend graduate level courses and pursue his Master of Science degree. Some of these courses were taught at PP&L, and concentrated in the field of Power Engineering.